FORELAND AND TRENCH SLOPE BASIN SANDSTONES OF THE GOOSE TICKLE GROUP AND LOWER HEAD FORMATION, WESTERN NEWFOUNDLAND

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by

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ABSTRACT

Two major Ordovician siliciclastic units can be recognised in western Newfoundland: the parautochthonous Goose Tickle group (Llanvirn - ?Llandeilo), and the allochthonous Lower Head Formation (Arenig - Llanvirn). This study has resulted in the distinction of two units within the Goose Tickle group: the American Tickle and Mainland formations. The Howe Harbour member has also been newly recognised within the American Tickle formation.

All three formations are dominated by turbidites, ranging from the deposits of low and moderate concentration flows for the relatively sand-poor American Tickle formation, to high concentration flows for the sand-rich Mainland and Lower Head formations. The American Tickle formation was deposited under anoxic conditions in a foreland basin with at least two different sediment input points. The turbidites and debris flows of the Howe Harbour member were locally shed in front of faults generated by allochthons (Taconic Allochthons) which were advancing over the eastern margin of the basin. The Mainland formation was deposited in the southern part of the same basin, but in much closer proximity to a third sediment input point, and has complex characteristics related to unusual local topography. The Lower Head Formation exhibits complex facies variations and was deposited in a confining trench slope basin or basins.

Although all three units are petrographically similar, the Lower Head Formation is distinct in that it contains a higher feldspar content and a lower lithic fragment content than the Goose Tickle group. Petrographic characteristics are consistent with mixed sources for all units. While many of the sources can be related to lithologies now present in the Taconic Allochthons, there is no lithology in the allochthons which can be

related to felsic volcanic grains and rounded microclines. Mixing of detritus in a now destroyed basin or basins is implied, and the overall provenance suggests supply of sediment from a major and complex area of uplift of which the Taconic Allochthons are only a small and incomplete remnant. This uplifted area included passive margin sediments, possibly Grenville basement and a major arc terrane which may have been compressed prior to erosion.

Geochemical analyses also indicate mixed sources and demonstrate that the Lower Head Formation is distinct from the Goose Tickle group. Comparison of the behaviour of trace elements between the units suggests that weathering of source areas may have been more intense during the Llanvirn than the Arenig.

Although western Newfoundland foreland and trench slope sediments are broadly typical of their tectonic setting, variations in sedimentology do exist along the length of the system, and they differ in subtle respects from analogous units in Quebec, supporting the concept of variations in tectonic style along the length of the Appalachian basin.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Although western Newfoundland is considered a classic area for study of Appalachian geology, there is still considerable disagreement as to the details of orogenesis. Sandstone provenance studies have been used elsewhere to study the fine scale details of compressional orogenesis (e.g. Hiscott, 1979; Dorsey, 1988; Thornburg and Kulm, 1987), but these require a sound stratigraphic framework, and an understanding of the regional depositional setting. No serious attempt has been made to incorporate information from western Newfoundland sandstones into tectonic models, and hence this thesis represents an attempt to provide this information at a regional scale.

1.2 REGIONAL GEOLOGIC SETTING

The Appalachian Orogen is an elongate, deeply eroded belt of deformed Paleozoic rocks which extends from Newfoundland to Alabama along the eastern seaboard of the North American continent. It is continuous with the Ouachita Orogen to the southwest. Prior to the opening of the modern Atlantic Ocean, the Appalachian Orogen was also continuous with orogenic belts in East Greenland, Britain, and Scandinavia (Caledonian Orogen) and West Africa (Mauritanides) (Williams, 1984). The Appalachian Orogen provides a record of latest Precambrian to Middle Paleozoic ocean opening and closing, terrane accretion, and continental collision. The island of Newfoundland, located in the northeast segment of the Appalachians, provides one of the best exposed cross sections

through the orogen. This study is mainly concerned with Ordovician sandstones, which are related to ocean closing, in western Newfoundland.

The Canadian portion of the Appalachian Orogen was divided into a number of tectonostratigraphic zones by Williams et al. (1974). These zones were defined on the basis on contrasting Ordovician and earlier stratigraphy. The zonation scheme was revised by Williams (1978) and expanded to include the entire Appalachian Orogen. The present tectonostratigraphic framework for the orogen is based on the scheme of Williams (1978) as modified by Williams et al. (1988), Williams et al. (1989), and Colman-Sadd et al. (1990) (See figure 1.1).

The Humber Zone is continuous along the western edge of the orogen and is a sinuous belt of mainly sedimentary rocks which were deposited on Grenville basement on the northwestern margin of the Paleozoic Iapetus Ocean (Harland and Gayer, 1972). The Iapetus Ocean was created by rifting during the Late Proterozoic or Early Cambrian (Williams, 1979; Hatcher, 1987; Williams and Hiscott, 1987; Lindholm and Casey, 1989). Collision of the continental margin with a volcanic arc terrane occurred during the Middle Ordovician Taconic Orogeny. The Humber Zone provides a record of the entire cycle from rifting to orogenesis. The sinuous outline of the Humber Zone may represent an original orthogonal pattern of transform faults which existed from the time of rifting of the margin (Thomas, 1977).

East of the Humber Zone, all of Williams' (1978) zones are now viewed as

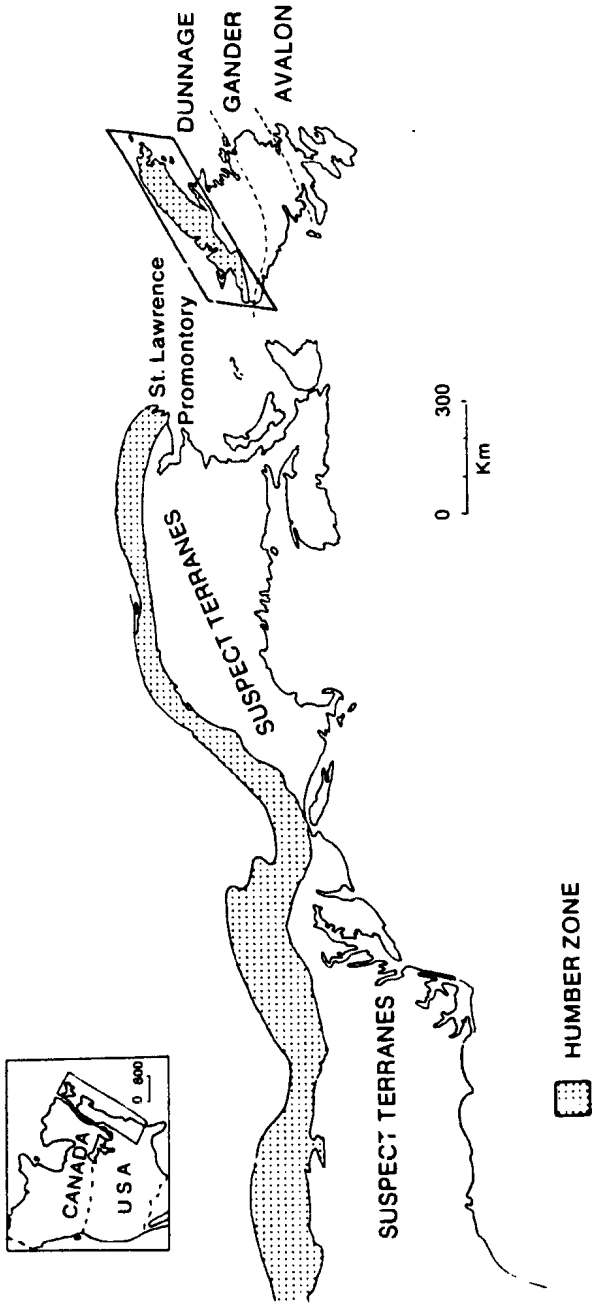

Figure 1.1: The Humber Zone and suspect terranes in the Newfoundland segment of the Appalachian Orogen, showing the location of the study area.

pieces of a mosaic of 'suspect terranes' (Coney et al, 1980; Williams and Hatcher, 1982, 1983; Williams, 1984) which have been accreted onto the ancient continental margin. In Newfoundland, three major terranes are present, the Dunnage, Gander, and Avalon zones. The Dunnage Zone lies immediately southeast of the Humber Zone and consists of arc-related volcanics and marginal basin sediments overlying ancient oceanic crust (Williams, 1979; Williams et al., 1988; Cawood et al., 1988). Ophiolites (the Bay of Islands Complex and the White Hills Peridotite) which have been transported onto the Humber Zone have also been included in the Dunnage Zone by Williams et al. (1989) and Colman-Sadd et al. (1990). The Dunnage Zone has been interpreted as a probable remnant of the Iapetus Ocean. Farther eastward is the Gander Zone, a sequence of mainly siliciclastic metasedimentary rocks which may represent the ancient southeastern margin of the Iapetus Ocean. Still farther east is the Avalon Zone which exhibits pre-Paleozoic deformation and appears to have a history unrelated to that of the Humber Zone (O'Brien et al., 1983). The Dunnage and Gander terranes are inferred to have been accreted to the margin by the Middle Ordovician, whereas the Avalon Terrane was accreted by the Devonian at the latest, (Williams, 1984) but may have been in place much earlier. Several publications suggest that Avalon rocks are stratigraphic basement to the Gander Zone (O'Brien et al., 1991; Colman-Sadd et al., 1992).

According to Marillier et al. (1989), the Humber Zone is underlain by crustal material of continental affinity known as the Grenville Block. The Gander Zone is underlain by a subsurface region known as the Central Block. However, the Humber/Dunnage and Dunnage/Gander boundaries are not present at depth in the

subsurface, implying that the Dunnage Zone is allochthonous with respect to both the Humber and Gander Zones. The Avalon Zone is underlain by crust which has a different seismic signature than either the Humber or Gander Zones (Marillier et al., 1989). It should be noted, however, that subcrustal blocks cannot be unambiguously related to the surface tectonostratigraphic zones.

Three main phases of deformation have affected the Appalachian Orogen, and the effects of all three are visible in Newfoundland. The first phase, the Taconic Orogeny, occurred during the Early to Middle Ordovician, and is inferred to be related to the onset of subduction and closure of the Iapetus Ocean (Williams, 1979). The Silurian-Devonian Acadian Orogeny may represent the final collision of the European continent Baltica with the North American continent Laurentia. The Carboniferous Alleghenian event involved a greater component of convergence in the southern section of the Appalachian Orogen than in Newfoundland, and occurred as a result of the collision of the African continent with Laurentia.

Two major factors affected sedimentation on all of the Laurentian continental margins during the Cambrian and Ordovician periods. The first was the position of the continental margin of the Iapetus with respect to the equator. This ranged from a latitude of approximately 30 degrees S in the Cambrian, to 10 degrees S by the middle Ordovician (Scotese et al., 1979). In addition, sea level rose throughout the Cambrian, dropped at the end of the Early Ordovician, and rose again in the later Ordovician (Fortey, 1984; Knight et al., 1991). In the initial phases of each transgression siliciclastic sediments were deposited. These are overlain by carbonate platform

sediments which were deposited in the very widespread warm shallow seas which existed around the margins of the continent (e.g. Dott and Batten, 1984). In the Humber Zone of western Newfoundland, evidence of rifting, margin destruction and terrane accretion is superimposed upon these more general characteristics (e.g. Williams, 1979, 1984).

1.3 TECTONIC SETTING OF THE HUMBER ZONE

Western Newfoundland is part of the Humber Zone, or miogeocline (Williams and Hatcher, 1982, 1983) which constitutes the Early Paleozoic western margin of Iapetus (Williams and Stevens, 1974). The western boundary of the Humber Zone was stated by Williams (1979) to be the western limit of Appalachian deformation. In practice, this boundary may be difficult to define; Stockmal and Waldron (1990) have raised the possibility that some of the relatively undeformed platform sequence may in fact be allochthonous.

In the Canadian Appalachians, the eastern boundary of the Humber Zone is the Baie Verte - Brompton line (Williams and St. Julien, 1982), a belt of steeply dipping, east facing ophiolites. The western part of the Humber Zone has been affected by Taconic and Acadian deformation, whereas its eastern margins near the boundary with the Dunnage Zone have been subject to polyphase metamorphism and deformation. In western Newfoundland, the main tectonic elements of the Humber Zone are as follows (see figure 1.2):

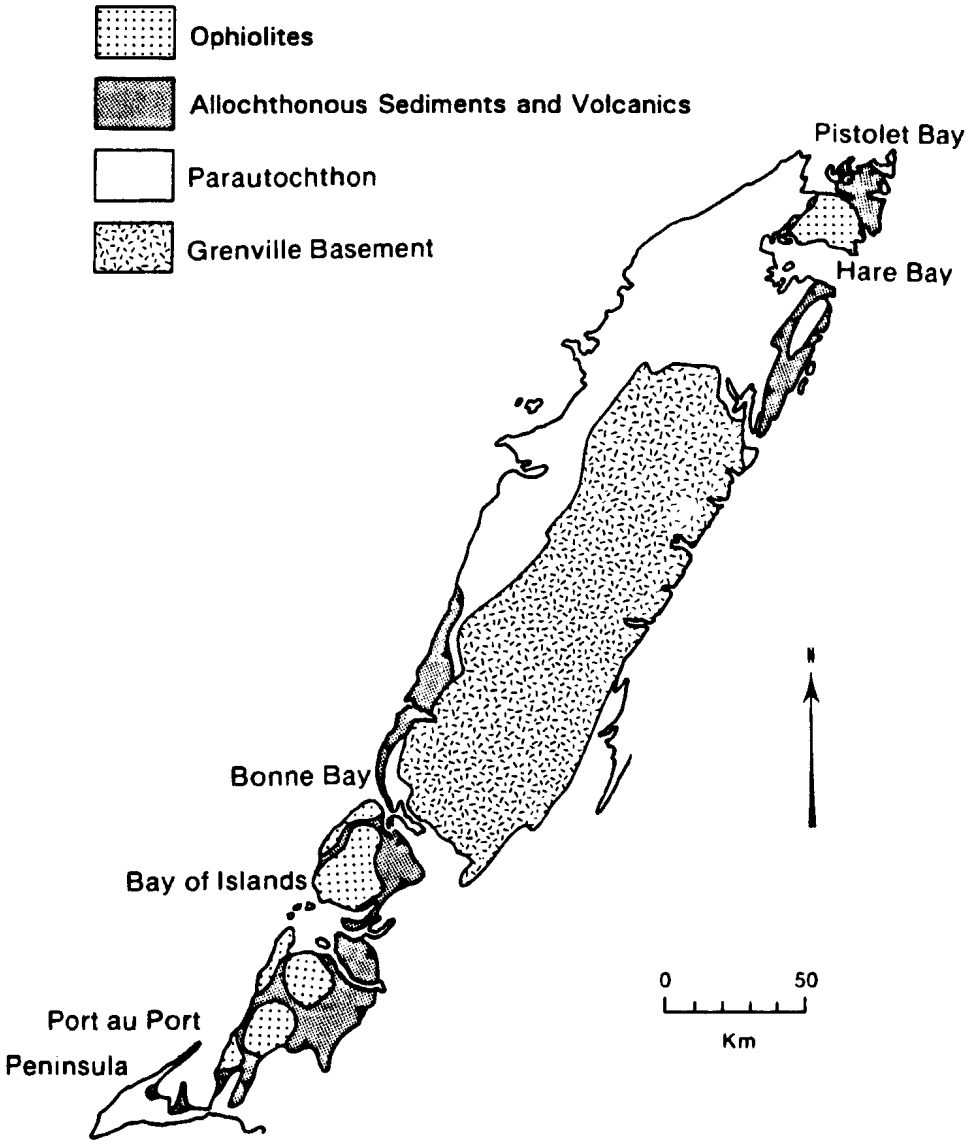

Figure 1.2 Tectonic elements of western Newfoundland.

1. Crystalline basement of the Long Range Complex which has been affected by Grenvillian (1100 Ma) deformation;

2. Parautochthonous Cambro-Ordovician sedimentary rocks that record a history of rifting, the development of a passive continental margin, and the initial phases of destruction of the margin. This succession is described in older literature as autochthonous but since parts of it may in fact have been transported a considerable distance (Stockmal and Waldron, 1990), the term parautochthonous is used.

The sedimentary rocks of this tectonic element have been traditionally described as 'autochthonous' (e.g. James and Stevens, 1982). Here the term 'parautochthonous' is used because they may have undergone variable degrees of transport, from less than 10 km (Grenier, 1990) to greater than 30 km (Stockmal and Waldron, 1990);

3. Allochthonous terranes (the Hare Bay and Humber Arm allochthons) consisting of stacked, fault-bounded slices of sedimentary rocks, volcanic rocks and ophiolites. The sedimentary rocks are contained within the lower structural slices of the these packages, and the volcanics and ophiolites constitute the upper slices. The allochthonous sedimentary rocks were deposited as offshore equivalents of the autochthonous sedimentary succession. The ophiolitic parts of the allochthonous terranes are considered to be isolated portions of the Dunnage Zone (Cawood et al., 1988; Williams et al., 1988).

1.4 STRATIGRAPHY OF THE HUMBER ZONE

1.4.1 The Parautochthon

Grenvillian basement is overlain unconformably by mainly siliciclastic rocks of the Labrador Group (Precambrian-Lower Cambrian; Cumming, 1983) (figure 1.3) which are products of Late Precambrian rifting and subsequent development of the passive margin of the Iapetus Ocean. During the Cambrian period, a laterally extensive, although narrow (Chow and James, 1987) shallow-water carbonate platform developed on the newly formed continental margin and remained stable until the Middle Ordovician. The platformal sequence consists of the Cambrian Port au Port Group (Chow, 1986), the Upper Cambrian-Lower Ordovician St. George Group (Knight and James, 1987; Williams et al., 1987), and the lower part of the Lower-Middle Ordovician Table Head Group (Klappa et al., 1980; Stenzel et al., 1990) (figure 1.3). The first indication of foreland basin development occurs in the St. George Group where a widespread unconformity marks the formation of a peripheral bulge associated with loading of the margin (e.g. Jacobi, 1981; Knight and James, 1987; Knight et al., 1991). Subsequent collapse of the platform caused deposition of deeper water limestones and olistostromal conglomerates of the upper, Middle Ordovician part of the Table Head Group (Stenzel et al., 1990). These are overlain by shales of the lower part of the Middle Ordovician Goose Tickle group (Quinn, in preparation; Stenzel et al., 1990) (figure 1.3). These shales represent the initial stages of siliciclastic infilling in the narrow (Bradley, 1989) axial region of a flexural foreland basin (Quinlan and

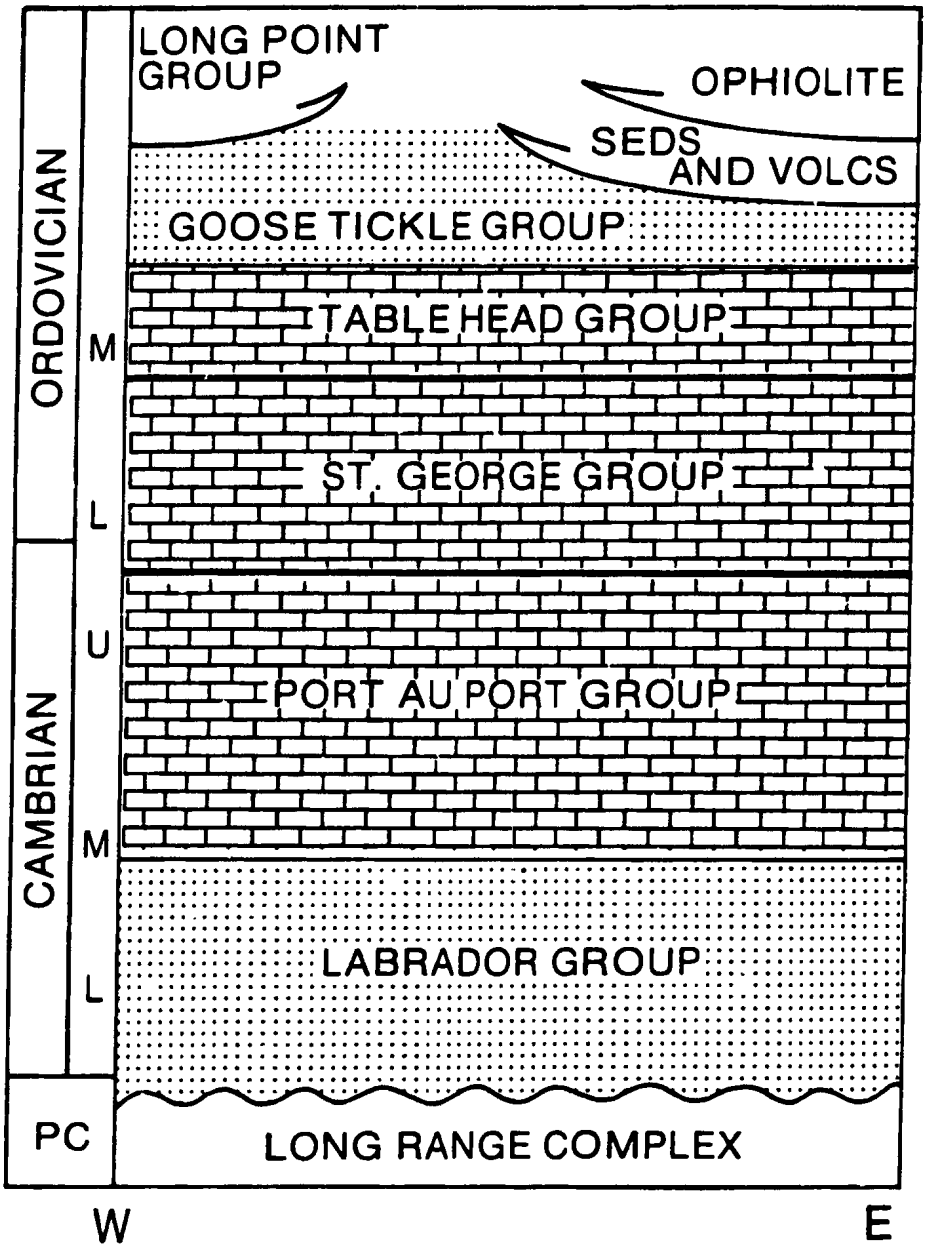

Figure 1.3: Generalised stratigraphy of western Newfoundland, after James and Stevens (1986); Klappa et al. (1980); Cumming (1983); Chow (1986); Knight and James (1987); Stenzel et al. (1990); and Quinn (in preparation).

Beaumont, 1984; Hiscott et al., 1986). The shales are overlain by flysch of the Llanvirn to latest Llandeilo or earliest Caradoc Goose Tickle group.

1.4.2 The Allochthons

The sedimentary strata of the Humber Arm and Hare Bay allochthons (figure 1.4) are interpreted as deep-water slope/rise deposits which are mainly coeval with the shallow-water parautochthonous succession (Williams, 1979). They consist of a lower siliciclastic sequence, a middle carbonate sequence and an upper siliciclastic sequence. The lower siliciclastic sequence includes the Maiden Point, Blow me Down Brook, Summerside, and Irishtown formations of ?Late Precambrian-Middle Cambrian age. The Maiden Point Formation is the oldest sedimentary unit in the Hare Bay Allochthon (Cooper, 1937; Tuke, 1968; Williams and Smyth, 1983). The Summerside Formation is the oldest unit in the coherent sedimentary sequence of the Humber Arm Allochthon (Stevens, 1965; Botsford, 1988) and is overlain by the Irishtown Formation. The Blow me Down Brook Formation may be a partial equivalent of the Summerside Formation, but is probably older, and is now isolated as a high structural slice in the sedimentary assemblage of the Humber Arm Allochthon (Quinn, 1985, 1986, 1988a,b; Lindholm and Casey, 1989; Cawood and Botsford, 1991).

The lower siliciclastic sequence is overlain by carbonate and shale deposits which are deeper water equivalents of the carbonate-platform deposits of the autochthon. These are the Cooks Brook Formation (Stevens, 1965, 1970; Botsford, 1988), a unit of thin bedded limestone turbidites and shales in the southern part of the

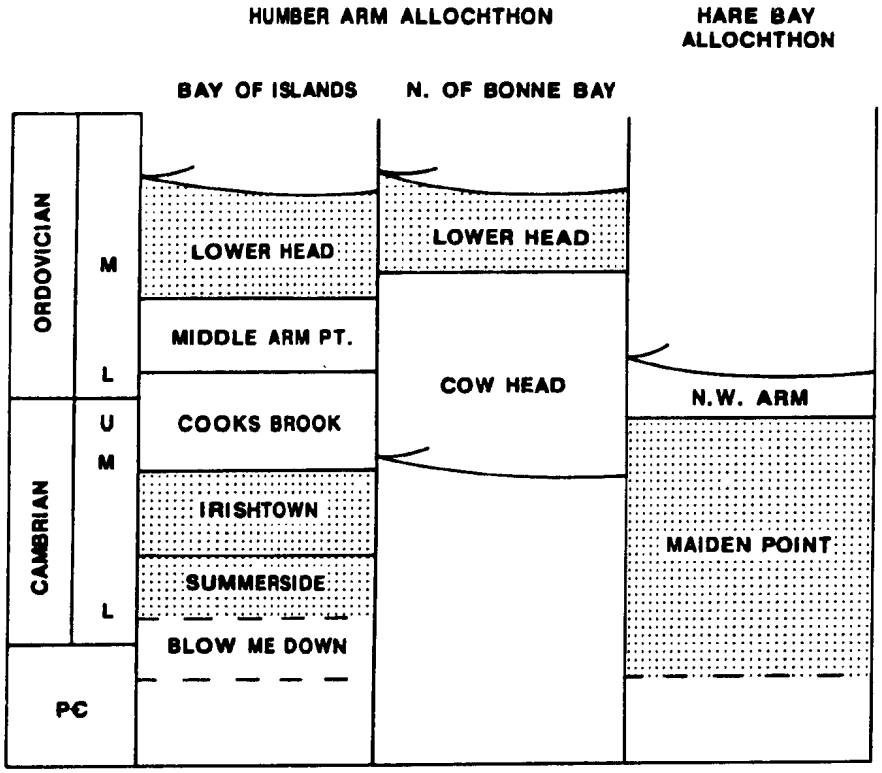

Figure 1.4: Generalised stratigraphy of the Humber Arm and Hare Bay allochthons. After Stevens (1965, 1970); Bruckner, 1966; Botsford, 1988; Williams and Smyth (1983).

Humber Arm Allochthon, and the spectacular limestone breccias and shales of the Cow Head Group (James and Stevens, 1986) in the northern part of the Humber Allochthon. The upward change from carbonate to siliciclastic deposition was gradual, particularly in the southern part of the Humber Arm Allochthon where the transition is represented by the Middle Arm Point Formation (Botsford, 1988). In the northern part of the Humber Arm Allochthon a transitional unit is not well developed and the carbonates are directly overlain by a unit of flysch, the Lower Head Formation (James and Stevens, 1986). Flysch deposits equivalent to the Lower Head Formation are present in the central and southern parts of the Humber Arm Allochthon but they have not been formally named. The base of the Lower Head Formation is slightly older (Arenig) than its parautochthonous counterparts (James and Stevens, 1986; Botsford, 1988). In the Hare Bay Allochthon, a gradual transition from carbonates to siliciclastics may also be represented within the structurally complex Northwest Arm Formation.

The allochthonous sedimentary suite is structurally overlain by discrete slices of volcanic rocks and ophiolites. Melange zones separating these structural slices are related to assembly and emplacement of the allochthons.

The allochthons are interpreted to have been assembled during eastward subduction (e.g. Church and Stevens, 1971; Williams and Hatcher, 1983; also see Jenner et al., 1991 for a reinterpretation of the Bay of Islands Ophiolite suite), accompanied by obduction of oceanic crust (upper structural slices) and transport of parts of the continental slope/rise (lower allochthonous slices) across the continental shelf.

Until recently, a hypothesis for the timing of the emplacement of the allochthons

was thought to be well established (Williams and Hatcher, 1983). This model held that the ophiolites were the first to move, accreting successive slices until the final emplacement of the allochthons as complete packages (Williams, 1979). It was thought that the sedimentary part of the Humber Arm Allochthon was in place by the Middle Ordovician as its leading edge appeared to be unconformably overlain by sediments of the neoautochthonous Caradocian Long Point Group (Rodgers, 1965; Cawood et al., 1988).

Now, however, the contact between equivalents of the Lower Head Formation and the Long Point Group has been reinterpreted as a thrust (Stockmal and Waldron, 1990). In addition, two conflicting theories have arisen as to the relative timing of emplacement of the sedimentary and ophiolitic parts of the Humber Arm Allochthon.

There is structural evidence that the ophiolites, which were formed during the period from 480 ma to 494 ma (Dunning and Krogh, 1985), were not emplaced together with the sedimentary slices (Schillereff, 1980). Cawood and Williams (1988) have suggested, again on structural grounds, that the final emplacement of the ophiolite may not have occurred until the Silurian or Devonian.

In contrast, Stockmal and Waldron (1990) have argued, on the basis of field mapping and seismic data, that major movements took place during the Acadian phase of deformation, transporting platformal sediments, allochthons and even the Grenvillian crystalline basement. In their view the Humber Arm Allochthon had previously been emplaced as a complete package. Stockmal and Waldron (1990) believe that the timing of emplacement of the ophiolite is constrained by the presence of ophiolitic detritus in

the Middle Ordovician Lower Head Formation and equivalents. Cawood and Williams (1988) did not address the issue of ophiolitic detritus in their discussion. Information provided in this thesis may have a bearing on this discussion.

There is general agreement that Acadian movement of the Long Range Complex has taken place, since parts of the basement overthrust the northern part of the Humber Arm Allochthon (Williams et al., 1985; Cawood and Williams, 1986; Grenier and Cawood, 1988; Grenier, 1990). The magnitude of transport inferred by these authors is far less than that suggested by Stockmal and Waldron (1990).

1.5 PREVIOUS WORK

1.5.1 Stratigraphic and Tectonic

Richardson (in Logan 1863) was the first to erect a stratigraphy for western Newfoundland from the Strait of Belle Isle to Bonne Bay (figure 1.2; Table 1.1, 1.2). He interpreted the sedimentary rocks of the region as a complete succession divisible into 16 units designated A to Q in order of decreasing age. Divisions O to Q are now known to be allochthonous equivalents of units A to N. Parautochthonous Ordovician sandstones of interest in this thesis were included with some allochthonous units in Richardson's division O.

A very extensive stratigraphic study was published by Schuchert and Dunbar in 1934, who again interpreted the succession as a continuous one. They defined three major groups of sandstone, the Labrador Series, the Long Point Series, and the Humber

RICHARDSON (1863)	SCHUCHERT & DUNBAR (1934)	CURRENT
O	Long Point Series	Long Point Group
O	Long Point Series	Goose Tickle Group
K-N	Table Head Series	Table Head Group
D-I	St. George Series	St. George Group
	March Point Series	Port au Port Group
A-C	Labrador Series	Labrador Group

Table 1.1: Equivalency of stratigraphic units of Richardson (1863) and Schuchert and Dunbar (1934) with current stratigraphic units in western Newfoundland.

Richardson (1863)	Sandstones included in division O of stratigraphic sequence.
Cooper (1937)	**Goose Tickle slates**, Hare Bay.
Betz (1939)	**Englee formation**, Canada Bay.
Troelson (1947)	**Gadd's Point slates**, Bonne Bay area.
Tuke (1966, 1968)	**Goose Tickle Formation**, Pistolet Bay area.
Stevens (1976)	**Mainland greywacke sequence**, Port au Port Peninsula.
Schillereff and Williams (1979)	**Mainland sandstone**, Port au Port Peninsula.
Williams and Smyth (1983)	Extended the **Goose Tickle Formation** to include the Pistolet Bay, Hare Bay and Canada Bay areas.
Williams et al. (1984)	**Sandbar formation**, Bonne Bay area.
Williams et al. (1985)	**Norris Point formation**, Bonne Bay Area. Dropped the term **Sandbar formation**.
Williams and Cawood (1986)	**Whale Back formation**, area south of the Bay of Islands.
Knight (1986)	Suggested that the **Goose Tickle Formation** was present in the Table Point area.
Quinn (1988)	Suggested that the **Mainland sandstone** was present in the Table Point area.
Lindholm & Casey (1989)	Suggested that the name **Goose Tickle Formation** be applied to all autochthonous or parautochthonous examples of easterly derived flysch in western Newfoundland.
Stenzel et al. (1990)	Quoted Quinn's unpublished informal terms **Goose Tickle group**, **Mainland sandstone** and **American Tickle formation**. Proposed the **Daniel's Harbour Member** within the **American Tickle formation**.
Quinn (In prep.)	Formal proposal of the **Goose Tickle Group**, **Mainland Formation**, **American Tickle Formation** and **Howe Harbour Member**.

Table 1.2: History of development of stratigraphic nomenclature for parautochthonous Ordovician sandstones of western Newfoundland.

Arm Series. The Labrador Series included rocks of Cambrian age. The Long Point Series was inferred to be of Middle Ordovician age but is now known to include both parautochthonous and allochthonous siliciclastic rocks of Middle and Late Ordovician age. The Humber Arm Series was thought to be the youngest unit of all (Middle or possibly Upper Ordovician) but the lower part of this series contained sandstones now interpreted as being of Cambrian age. The equivalencies of both Richardson's and Schuchert and Dunbar's units with modern parautochthonous units are shown in table 1.1.

Further advances required an understanding of the structural configuration of western Newfoundland which came about as a result of the work of Rodgers and Neale (1963), who recognised the existence of the allochthons in the region. Stevens (1970) built on the work of Rodgers and Neale (1963), and Wilson (1966) and included the parautochthonous Ordovician siliciclastics in a tectonic-stratigraphic framework which reflected a model of passive margin evolution and destruction. Stevens (1970) classified sandstones of western Newfoundland into Atlantic type and Pacific type flysch, and suggested that a reversal in provenance from west to east was indicated by the presence of chromite in all flysch of post-Arenig age. Particular attention was paid to the Humber Arm Allochthon where the sedimentary rocks were divided into lower quartzo-feldspathic flysch, carbonate flysch, and upper quartzo-feldspathic flysch. The Blow me Down Brook Formation (upper quartzo-feldspathic flysch) was described as an Ordovician unit containing ophiolite detritus which indicated that ophiolites were exposed to the east. The work of Stevens (1970) has provided the basis for all subsequent

sedimentary/tectonic models.

Stevens' (1970) classification of western Newfoundland sandstones and those of several subsequent workers (e.g. Quinn, 1986, 1988; Lindholm and Casey, 1989) reflected a genetic rather than a strictly lithostratigraphic approach. Correlations of sandstones in western Newfoundland have generally been problematic (Quinn, 1985, 1986, 1988a,b; Lindholm and Casey, 1989) and the disorganisation of the stratigraphic nomenclature does not reflect the current understanding of the regional tectonic significance of these units. The history of development of the stratigraphic nomenclature is outlined in table 1.2.

The potential confusion over the largely informal stratigraphic nomenclature which has proliferated for both allochthonous and autochthonous sandstones was sidestepped by Quinn (1986, 1988a), who offered a genetic classification of sandstones in western Newfoundland in relation to the then-current stratigraphic nomenclature. In this classification, which is similar to that of Stevens (1970), sandstones were divided into two main tectonic categories (Quinn, 1986, 1988a):

1) Upper Precambrian or Cambrian marine sandstones deposited as a result of rifting and initial development of a passive continental margin;

2) Ordovician marine sandstones deposited in an active margin setting.

Quinn (1986, 1988) subdivided these categories to emphasise that differences are to be expected between autochthonous sandstones and their equivalents which have been transported. The subdivisions are as follows:

1a) Autochthonous ?Precambrian-Cambrian rift related sandstones;

1b) Sandstones broadly equivalent to 1a which were deposited farther offshore in deeper water and have subsequently been transported over the ancient continental margin;

2a) Autochthonous Ordovician marine sandstones deposited in an active margin setting;

2b) Sandstones deposited in the same general tectonic setting as those in 2a and subsequently transported as part of an accretionary prism over the ancient continental margin.

Figures 1.5 and 1.6 show the areal distribution of each of the above subcategories.

The following points regarding the state of the stratigraphic nomenclature at the inception of this study are worthy of note.

1. The Lower Head Formation, defined in the northern part of the Humber Arm Allochthon by James and Stevens (1986), had not been formally extended south of Bonne Bay. It had been informally termed the Eagle Island formation by Botsford (1988) and Cawood et al. (1988), but it is unlikely that this name can be incorporated into the stratigraphic literature as it has been pre-empted (H. Williams, 1988, pers. comm.). However, the Eagle Island formation has been included as a formal term in subsequent papers (Cawood and Botsford, 1991). Lower Head equivalents in the Port au Port Peninsula had not been named.

2. No suggestion had yet been made as to how to incorporate the newly defined Blow me Down Brook Formation (Quinn, 1985, 1986, 1988a; Lindholm and Casey, 1989) into the general stratigraphy of the Humber Arm Allochthon, as it had not been incorporated into the informal stratigraphic revision of Botsford (1988).

3. The distinction between the Goose Tickle Formation and the Mainland sandstone was

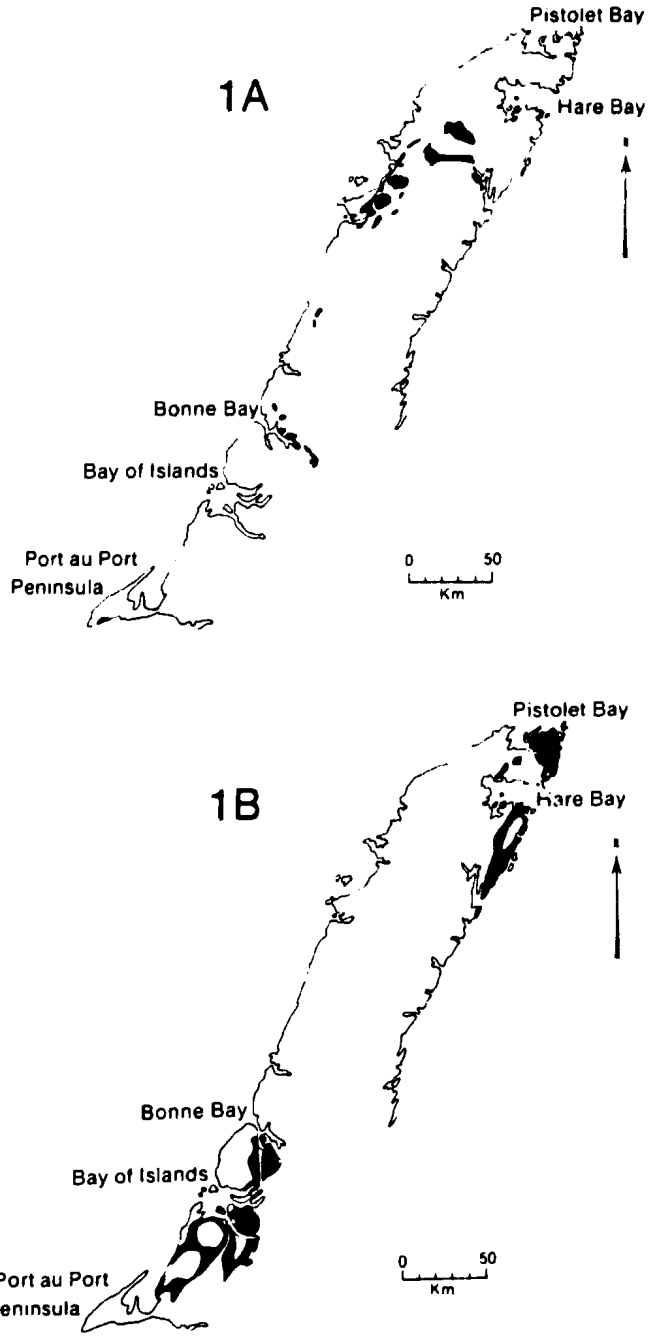

Figure 1.5: Distribution of category 1 sandstones in western Newfoundland (after Quinn, 1988a,b). A=parautochthonous sandstones; B=allochthonous sandstones.

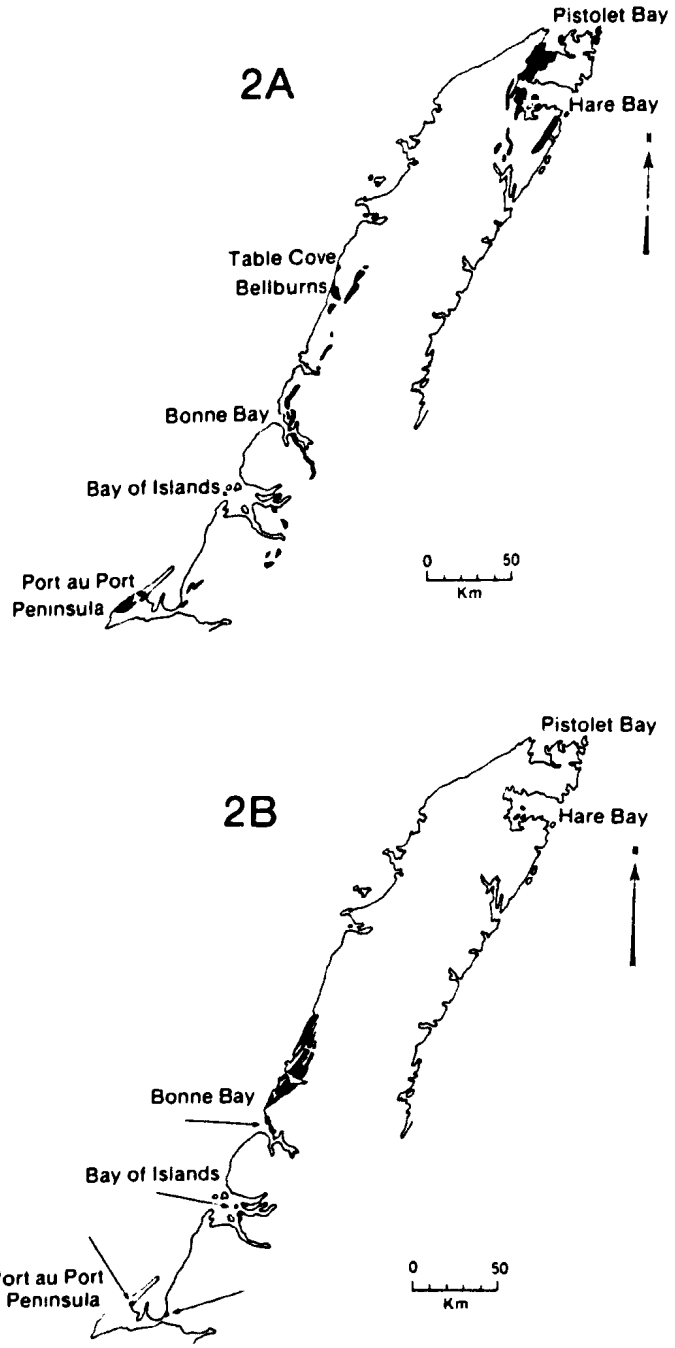

Figure 1.6: Distribution of category 2 sandstones in western Newfoundland. A=the Goose Tickle group; B=the Lower Head Formation (after Quinn, 1988a,b).

not clear (Knight, 1985; Quinn, 1988a; Lindholm and Casey, 1989), and in fact 'Mainland sandstone' (Schillereff and Williams, 1979), a widely used name, had never been formally proposed. The distinction between both of these units and the Norris Point formation (Williams et al., 1985) was also unclear. These problems have been rectified by Quinn (in preparation) as discussed in chapter 2 and the simplified stratigraphic nomenclature is shown in chapter 2, figure 2.1.

1.5.2 Sandstone Petrography and Provenance Studies - a Discussion

Sandstone petrography in western Newfoundland has been used for two purposes:
1. the distinction between superficially similar units in the Humber Arm Allochthon; and
2. the determination of provenance of Ordovician flysch.

The first general petrographic description of western Newfoundland sandstones was by Schuchert and Dunbar (1934) who noted that sandstones of both the Humber Arm and Long Point Series were arkosic and lithologically similar. Stevens (1970) defined a lower quartzo-feldspathic flysch (Cambrian) and an upper quartzo-feldspathic flysch (Ordovician) in the Humber Arm Allochthon, reinforcing the idea that two major sandstone units of rather similar aspect exist in western Newfoundland. Gonzalez-Bonorino (1979) carried out petrographic studies of samples from selected sandstone localities in the northern, central, and southern parts of the Humber Arm Allochthon. The central locality seemed to be significantly different lithologically from the others, but Gonzalez-Bonorino (1979) was unable to reach a conclusion as to the reason for the variation. Quinn (1985, 1986, 1988a), based on petrographic work in the central part

of the Humber Arm Allochthon, outlined a hypothesis wherein much of the sandstone which had previously been mapped as Ordovician flysch was reinterpreted as an isolated, structurally high slice of ?Precambrian-Cambrian sandstone. The hypothesis was supported on structural grounds by Waldron (1985), and was confirmed by Lindholm and Casey's (1989) discovery of Early Cambrian fossils in the unit. Using this interpretation the variation in petrographic data of Gonzalez-Bonorino (1979) is due to the fact that he equated two completely different units. The reinterpreted area included the type section of the Blow me Down Brook Formation, which had hitherto been regarded as a classic example of chromite-bearing Ordovician flysch.

Stevens (1970) inferred a reversal of provenance in the sedimentary succession of western Newfoundland and related this to the change from a passive-margin to an active-margin setting. He described three main sources for easterly derived allochthonous flysch in the Humber Arm Allochthon: a silicic intrusive source rich in microcline granite and sodic granophyre; ophiolites with gabbros, volcanic rocks and chromite-bearing ultramafic rocks; and sediments similar to the older part of the allochthonous sedimentary sequence. Stevens (1970) also reported detritus from all units of the allochthon in autochthonous flysch near the Hare Bay Allochthon.

Whereas Stevens (1970) clearly indicated that ophiolitic and sedimentary detritus was derived from the allochthons, no indication was given of a location for the granitic source, although Williams and Stevens (1974) suggested that Precambrian basement could have been a source. Stevens (1970) also suggested that the presence of ophiolite detritus - serpentinite, chromite, and pyroxene crystals (Stevens in Neale (1972)) - in Ordovician

flysch in western Newfoundland indicates that 'ophiolites ..... must have been exposed to erosion and at least partially above sea level even though the base was below sea level'. Based on this argument, he concluded that the ophiolites and part of the allochthonous sediments were emplaced as migrating islands or archipelagos with fringing reefs which also contributed detritus to the flysch.

Thus provenance information from sandstones was crucial in building a first plate tectonic model for the geological development of western Newfoundland. Since the publication of this model, there have been few detailed quantitative studies of any sandstone unit in western Newfoundland. One exception to this is the work of Gonzalez-Bonorino (1979), on sandstones of the Humber Arm Allochthon, who noted a large proportion of albite in his samples. This he related to a metamorphic source. The interpretations of Gonzalez-Bonorino must be regarded as suspect since he failed to recognise that he was dealing with both Cambrian and Ordovician units (Quinn, 1985).

Quinn (1985) point-counted a suite of samples from two units in the Humber Arm Allochthon in the Bonne Bay area. One of these units had previously been thought to be correlative with the Blow me Down Brook Formation, but instead was interpreted on solely petrographic grounds to be a Cambrian unit with a westerly provenance (Sellars formation). Quinn (1985) also provided data on the Barters formation which is an equivalent of the Irishtown Formation in the Bay of Islands area.

Schwab (1991) has recently undertaken a regional quantitative petrographic study of various sandstone units across Newfoundland with a view to investigating whether

sandstone petrology could constrain tectonic models for the evolution of the entire island of Newfoundland. Schwab (1991) was unable to distinguish, on the basis of sandstone provenance, between a simple model of ocean opening and closing, and a model based on accretion of suspect terranes. Schwab (1991) grouped his sandstones in 'suites', those relevant to this thesis being one from the 'autochthonous Humber Zone', and three from the allochthonous Humber Zone. Schwab (1991) erred in describing the Goose Tickle Formation and Mainland sandstone as 'Humber Arm allochthonous' along with the Lower Head Formation and the Eagle Island sandstone. Equally serious is his inclusion of the Gadd's Point Formation (a Goose Tickle equivalent) in Cambrian units of the Humber Arm Allochthon. Since presumably his reason for distinguishing allochthonous from autochthonous deposits was to determine whether equivalent deposits had a distinct petrographic signature, these errors could have significantly affected his conclusions. Data presented in this thesis demonstrate a general similarity between the parautochthonous and allochthonous Ordovician sandstones, and Schwab's (1991) overall conclusions are unaffected.

The utility of provenance studies has been demonstrated for Ordovician flysch units in other parts of the Canadian Appalachians. Hiscott (1978) undertook a detailed provenance study of the Tourelle Formation, an allochthonous Arenig flysch located in the Quebec Appalachians. Assuming from other considerations a southeast dipping subduction zone (see Williams and Stevens (1974) for a summary of the evidence), Hiscott (1978) was able to relate the detrital content of the Tourelle Formation to the tectonic history of the area with a considerable degree of detail. He concluded that acid

volcanic fragments and fresh albite were related to an ensialic arc associated with the closing of the Iapetus Ocean - tentatively identified with the Cambrian-Middle Ordovician Tetagouche Volcanics of New Brunswick. Chromite grains and other mafic heavy minerals were considered to have been derived from an obducted ophiolite sheet.

Hiscott (1984) reviewed the available literature on modal proportions of framework grains in both allochthonous and autochthonous Ordovician flysch throughout the Appalachians, and incorporated trace element geochemical data from all of these units. Hiscott (1984) came to the general conclusion that since chromite and related trace elements are absent in the U.S. Appalachians, ophiolite obduction was a minor feature of the U.S. Appalachians during the Taconic Orogeny. Other notable work on the provenance of related sandstones includes that of Enos (1969) on the Cloridorme Formation in Quebec. The Cloridorme Formation is a parautochthonous flysch of mainly Caradoc age (Hiscott et al., 1986). Ko (1985) expanded on the work of Enos, and in addition provided a comprehensive review of petrographic characteristics of sandstones in the Quebec Appalachians. Ko (1985) concluded that several sources contributed to the Cloridorme Formation including argillaceous limestone, limestone conglomerate, feldspathic sandstone, quartzo-feldspathic schist, ophiolite, shale melange, and calc-alkaline volcanic fragments (although it is unclear how he could have identified the latter two sources in thin section). Most of these sources were identified with accretionary complexes although Ko (1985) also suggested some input from an uplifted cratonic source.

1.6 CURRENT HYPOTHESES

According to current models for the evolution of the geology of western Newfoundland, older clastic sediments (category 1) were deposited in relatively shallow marine shelf environments or as submarine fans on the continental slope/rise (Hiscott et al., 1984; Lindholm and Casey, 1989). The younger clastics (category 2) are interpreted by Hiscott et al. (1986) as flysch which was deposited in an elongate foreland basin (Quinlan and Beaumont, 1984). Similar basin fill flysch units are present along the length of the Appalachian Orogen although the ages of the units vary (Hiscott, 1984). According to Quinlan and Beaumont (1984) and Hiscott et al. (1986), the foreland basin was formed as a result of load induced subsidence of the continental margin as it was driven towards an active, or recently active, oceanward dipping subduction zone.

Hiscott et al. (1986) suggested that one of the few modern analogies for the Appalachian foreland basin may be the depressed northern margin of Australia (Banda Arc/Timor Trough - Hamilton, 1979), an analogy also made by Ko (1985). Karig et al. (1987) and Bradley (1989) have also utilised the Timor analogy and in particular Bradley (1989) has used it extensively.

Bradley (1989) has defined the axial zone of a foreland basin as the region between the turbidite front (transition from shales of the outer slope to turbidites) and the thrust front. The width of the axial part of the foreland basin in the Appalachians has been estimated by Bradley (1989) as about 15 km based on an analogy with the modern Timor foredeep. Hiscott et al. (1986) independently estimated that the foredeep basin in the Quebec area was only a few tens of kilometres wide at its deepest axial levels, and

may also have been segmented by structural highs at a high angle to the basin axis (Hiscott et al., 1986). In Newfoundland, the platformal part of the margin upon which the foreland basin developed is thought to have been fairly narrow (Chow and James, 1987).

Autochthonous Ordovician flysch in Newfoundland is separated from similar units in Quebec by the St. Lawrence Promontory (Thomas, 1977; Williams, 1978) and is somewhat older than these units (Hiscott et al., 1986). The age difference has been taken by Hiscott (1984) to indicate north - south diachronous closure of the Iapetus Ocean, but Bradley (1989) has suggested that a different arc may have collided with the continental margin in Newfoundland, and that the rest of the Appalachians underwent diachronous collision from south to north.

Since there are contrasts between Newfoundland flysch and Quebec flysch in terms of age and relative position along the length of the orogen, narrow comparisons between flysch units in Newfoundland and units elsewhere in the Appalachians may not be appropriate, as was also suggested by Hiscott (1978). Prior to this study, depositional models for Ordovician flysch in western Newfoundland were sketchy at best and were arrived at by implicitly making comparisons with better known Quebec examples. Little progress on specific details has been made since the work of Stevens (1970). Most subsequent researchers have reiterated the interpretation of Stevens (1970), and have emphasised the presence of chromite detritus in the sandstones (e.g. Williams 1979; Cawood et al., 1988). The adjective 'chromite-bearing' has frequently been used to describe the flysch (e.g. Cawood et al., 1988), and the fact that its bulk composition is

quartzo-feldspathic has been largely ignored. Where the quartzo-feldspathic nature of the flysch has been pointed out, reference has been made to Hiscott (1978) who concluded that quartzo-feldspathic detritus in the Tourelle Formation of Quebec was derived from older allochthonous sediments, or to Stevens (1970) who simply stated that the Taconic allochthons were a source of detritus (Stevens, pers. comm., 1987; Hiscott, pers. comm., 1988). The popular idea that the flysch in Newfoundland progressively 'transgressed' (prograded) across the margin from east to west was suggested by Williams and Stevens (1974), and was repeated by Botsford (1988). and Cawood et al. (1988), but Quinn (1988 a, b, c) has called this hypothesis into question.

1.7 SCOPE AND PURPOSE

This thesis presents the results of an investigation into the depositional setting, provenance and possible sources of Ordovician flysch (foreland basin deposits) of western Newfoundland.

The study as originally designed had a twofold purpose:

a) To refine the existing stratigraphic nomenclature for Ordovician sandstones in western Newfoundland, which was disorganised and largely informal; and

b) To determine provenance of the Ordovician flysch in this region. Particular emphasis was placed on a clarification of the influence of nearby allochthonous slices on detrital composition.

Since the object was a regional investigation of flysch provenance, both allochthonous and autochthonous units of Ordovician flysch were included in the study.

In addition, six Cambrian units were studied to test the hypothesis that their equivalents could have been source rocks for Ordovician flysch. However, since this approach required study of a large area, and a proportionately large number of units, no detailed investigation of any aspect could be carried out.

To avoid bias, no a priori assumptions were made regarding detrital components of the sandstone and early comparisons with Cambrian and Quebec units were avoided. Bulk compositional characteristics and general field relationships of the sandstones have been emphasised.

At the inception of this study, it was envisaged that quantitative petrography and the determination of provenance would be the main focus of the project, but the determination of provenance using quantitative methods is meaningless without a well-understood stratigraphic framework and an understanding of the basinal context of the units involved (Ricci Lucchi, 1985). The construction of this framework occupied more time than the author anticipated, and with the number of units involved in the study it was soon clear that a quantitative study of the rigour which was originally planned would unfeasible in the time allowed. Thus the quantitative studies present below must be considered of a reconnaissance nature only.

Despite these shortcomings, the synthesis of stratigraphy, facies and basin analysis, petrography, geochemistry, and regional geology presented here is still sufficient to provide a more sophisticated provenance analysis for Ordovician flysch than has previously been available.

1.8 GENERAL METHODOLOGY

1.8.1 Refinement of Nomenclature and Basin Analysis

Refinement of nomenclature and basin analysis involved eight months of fieldwork in 1985, 1986 and 1987, and the measurement and description of approximately 3000 m of section of which about 2000 m of selected examples are presented in this thesis. This part of the study resulted in the definition of three lithostratigraphic units of Ordovician flysch. Cambrian sandstone localities were also visited but sections were not measured. Six hundred samples of both Ordovician and Cambrian sandstones were collected for further study. An additional 30 samples were provided by Dr. N. James and Dr. H. Williams.

1.8.2 Determination of Provenance of Ordovician Flysch

A number of different methods, which were used to determine provenance, are outlined below.

Both qualitative and quantitative petrographic analysis were involved in the evaluation of all three newly defined units of Ordovician flysch. This involved qualitative description of approximately 200 thin sections, and staining and point counting of framework grains in 65 thin sections which were selected as being representative of the various units.

Bulk mineralogy of 20 selected samples was identified by X-ray Diffraction. In addition, 25 samples were studied under the Scanning Electron Microscope (SEM), using the backscattering mode. Use of the Energy Dispersive Spectrometer (EDS) facility

enabled qualitative characterisations of individual minerals. Cathode luminescence petrography was also carried out on selected thin sections to verify observations regarding alteration patterns in feldspars. All of the above aspects of the study were carried out at Brandon University.

Specific minerals from 12 samples were analysed with the electron microprobe at the University of Saskatchewan and the University of Manitoba. Minerals analysed included chlorite, chromite, plagioclase feldspar, and potassium feldspar.

The bulk chemistry of 107 samples was obtained by analyses for major elements (Atomic Absorption Analysis and Inductively Coupled Plasma Atomic Emission Spectrometry), trace elements (Neutron Activation Analysis and X-ray Fluorescence), and some rare earth elements (Inductively Coupled Mass Spectrometry and Neutron Activation Analysis). Details of which samples were analysed by which methods are given in appendix 4. Most of the analyses were carried out by Activation Laboratories, Ancaster, Ontario, and a small number of analyses were made at Memorial University.

Cambrian sandstones were investigated by the same methods as above to evaluate their potential as source rocks for Ordovician flysch.

Details of specific methodologies for all of the above approaches are given in the appropriate chapters and appendices.

1.8.3 Terminology

Where directional terms such as westward and eastward are used, they refer to present geographical coordinates.

Although a necessary part of this study was the clarification and refinement of stratigraphic nomenclature, the names American Tickle formation, Goose Tickle group, and Howe Harbour member will be shown with their lithostratigraphic designators in lower case letters, as a formal stratigraphic nomenclature cannot be proposed in a thesis (North American Stratigraphic Code, 1983).

The term flysch will here refer simply to deep water deposits which are syn-orogenic according to the definition of Blatt et al. (1991).

Bed thicknesses will be expressed as thin, medium, etc. with the quantitative meanings of these terms after Ingram (1954), i.e. very thick-bedded (>1 m); thick-bedded (30 - 100 cm); medium-bedded (10 - 30 cm); thin-bedded (3 - 10 cm); very thin-bedded (1 - 3 cm); Thickly laminated (0.3 - 1 cm); thinly laminated (<0.3 cm).

The term facies will be used in the same sense as Pickering et al. (1986) to describe a body of rock with specific descriptive physical, chemical and biological characteristics. In this thesis, emphasis will be placed on physical characteristics.

1.9 ACKNOWLEDGEMENTS

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CHAPTER 2

REGIONAL FIELD RELATIONSHIPS AND STRATIGRAPHY

2.1 INTRODUCTION

At the inception of this project, parautochthonous Ordovician sandstones of western Newfoundland had not been incorporated into a regional stratigraphic framework. Some of the allochthonous sandstones have been included in a stratigraphic scheme (James and Stevens, 1986), others have not. As a result of this study a formal proposal for a revision of the stratigraphic nomenclature of Ordovician parautochthonous sandstones has been prepared (Quinn, in prep.). The recommendations will include the elevation of the old Goose Tickle Formation to group status, and new names proposed will include the American Tickle formation and the Mainland formation, both to be included in the Goose Tickle group. A new member, the Howe Harbour member, has also been recognised within the American Tickle formation. Also included in this study is the allochthonous Lower Head Formation.

None of these units have been subjected to a detailed paleontological study, but general age relationships are known and available paleontological information may also be of use in evaluating the possible westerly decrease of the age of the base of these sandstones.

The relationship between a sandstone unit and adjacent units is particularly

important in a provenance study, as rocks or sediments of similar composition to these units may have provided identifiable detritus to the sandstones. Likely sources of detritus in the Goose Tickle group and Lower Head Formation include rocks similar to older units which stratigraphically underlie them and lithologies similar to those in allochthonous terranes which now structurally overlie them.

In this chapter, a summary of the current stratigraphy, and a general description of both parautochthonous and allochthonous Ordovician sandstones will be given along with a review of the available paleontological information. The chapter will concentrate on the units and their spatial or stratigraphic neighbours. It will be shown that, on the basis of fieldwork alone, coarse detritus in two of the three Ordovician sandstone units can be traced to immediately adjacent rock units. The data gathered in this chapter will be used as a basis for a more detailed discussion in chapter 3 of the sedimentology and the basinal context of the units.

2.2 THE DISTRIBUTION AND STRATIGRAPHY OF ORDOVICIAN SANDSTONES IN WESTERN NEWFOUNDLAND

The general distribution of sandstones in western Newfoundland, classified according to Quinn (1988a,b) (see chapter 1) is shown in figures 1.4 and 1.5. The Ordovician sandstones (category 2) are either parautochthonous (category 2a) or allochthonous (category 2b). Cambrian sandstones (category 1) were investigated solely to evaluate their potential as sources of sand-sized detritus and hence they will be described in chapter 6. Measured sections and descriptions of selected localities are

provided in appendix 2.

2.3 PARAUTOCHTHONOUS ORDOVICIAN SANDSTONES

The stratigraphy of the Middle Ordovician parautochthonous siliciclastic sequence, as revised by Quinn (in prep), is shown in figure 2.1. The sequence is now referred to as the Goose Tickle group (Quinn, in prep), which contains three formations: the Black Cove Formation, the American Tickle formation, and the Mainland formation. The main modifications to the previously existing stratigraphy (see table 1.2) include the elevation of the Goose Tickle to group status, the formal delineation of the Mainland formation, and the introduction of a new unit, the American Tickle formation, which encompasses the former Goose Tickle formation and other informal units (see table 1.2). The American Tickle formation contains two distinctive members: the Daniel's Harbour Member, proposed by Stenzel et al. (1990), and the Howe Harbour member (Quinn, in prep). The Black Cove Formation, which was formerly assigned to the Table Head Group by Klappa et al. (1980), was reassigned by Stenzel et al (1990) to the Goose Tickle group (Quinn, in prep), thus making the boundary of the Table Head/Goose Tickle groups the onset of deposition of predominantly siliciclastic sediments.

According to the definition of Quinn (in prep), the Mainland formation is now restricted to the Mainland area (appendix 1, location map 1), and the American Tickle formation extends almost the entire length of the Northern Peninsula from Pistolet Bay to northeast of the Port au Port Peninsula.

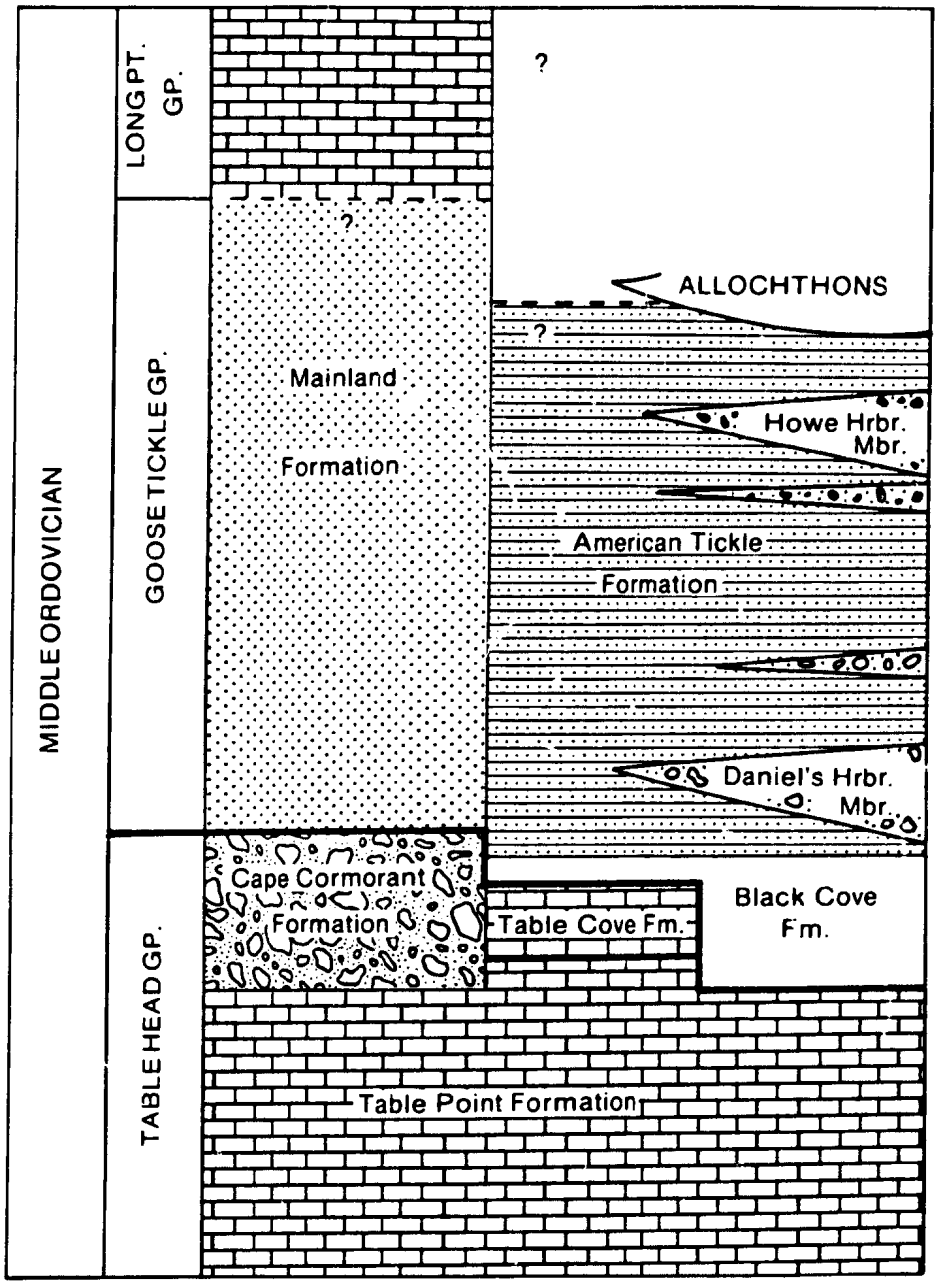


Figure 2.1: Generalised stratigraphy of the Table Head and Goose Tickle groups. After Stenzel et al. (1990) and Quinn (in prep.). The controversial contact between the Mainland formation and the Long Point Group is shown as a dotted line.

2.3.1 The Black Cove Formation

The Black Cove Formation (Klappa et al., 1980; Stenzel et al., 1990) is the lowermost formation in the Goose Tickle group. At different localities, it overlies either the Table Point Formation or the Table Cove Formation of the Table Head Group. It is not present on the west coast of the Port au Port Peninsula. The Black Cove Formation consists of a thin (4 - 22 m) unit of dark grey non-calcareous shales (Stenzel et al. 1990).

The base of the Black Cove Formation marks the base of the Goose Tickle group, and was defined by Stenzel et al. (1990) as the base of the first black non-calcareous shale above the last thin limestone bed of the top of the Table Cove Formation of the Table Head Group.

2.3.2 The American Tickle formation

The American Tickle formation is a unit dominated by silty argillite with minor sandstones. It is named for its occurrence at American Tickle in Hare Bay (appendix 1, location map 4). The unit extends from Pistolet Bay to the Black Cove area just northeast of the Port au Port Peninsula, although from Bonne Bay to the Port au Port Peninsula it is very poorly exposed. The type section is located at Goose Tickle (appendix 1, location map 4) in Hare Bay.

2.3.2.1 Lithologic Character

The American Tickle formation is a mainly fine-grained siliciclastic unit with

minor limestone breccia and polymict conglomerate. Despite difficulties in estimating thicknesses (see below), the American Tickle formation is divisible into lithological packages.

The American Tickle in its type area (Goose Tickle, see appendix 1, location map 4; appendix 2, section A2.1.1 for measured section) is mainly characterised by green silty argillite. Massive silty horizons are up to 50 cm thick, but mean thickness is about 20 cm. Interbedded with the argillite are black mudstone bands up to 1 cm thick which are between 4 and 15 cm apart. These dominant lithologies are interbedded in places with resistant, calcareous, tan weathering fine- to medium-grained sandstones. Sandstone beds have a mean thickness of about 30 cm and are commonly amalgamated; the deposits of single flows are about 15-25 cm thick. Common sedimentary structures in the sandstones are graded bedding, parallel laminations, ripple or ripple drift cross-lamination, and convolute laminations. These structures are contained in partial or complete Bouma (1962) sequences. Flute and load casts are also common. The tops of the beds are commonly marked by asymmetric ripple marks with wavelengths of 20-50 cm.

Another conspicuous lithology at the type section is thin, tan weathering, discontinuous, fine sand which occurs in lenses with irregular ripple laminae, and convolute laminae. These lenses have a mean thickness of about 5 cm and are regularly interbedded at 5 to 20 cm intervals with the silty argillite. The uppermost part of the section is poorly exposed, but near the contact with the Northwest Arm Formation there are at least two beds of conglomerate of the Howe Harbour member (see section

2.3.2.6). The conglomerates are not completely exposed, but are probably less than 1 m thick.

2.3.2.2 Structure and Thickness

The American Tickle formation is generally deformed at all localities, except those in the extreme west, as a result of its proximity to the bases of the Humber Arm and Hare Bay Allochthons. In the Hare Bay and Pistolet Bay areas, the American Tickle formation is deformed in open (westwards away from the Hare Bay Allochthon) to tight (eastwards towards the allochthon) NE to SW trending folds, with a moderate to strong associated cleavage (Knight, 1986b).

In the Table Cove area where Quinn (in prep) defined a reference section (appendix 2, section A2.1.3), the unit is less deformed, being mainly affected by minor folding and east-west trending tear faults which were related by Grenier (1990) to east-directed thrusting in the area. American Tickle lithologies commonly form the matrix to melanges at the bases of the allochthons, and much of what has been mapped by Williams and Cawood (1988) as melange in the area north of Bonne Bay is mainly chaotic American Tickle formation.

Because of the structural complexity of the American Tickle formation, an accurate thickness, even of the formation stratotype, cannot be obtained (appendix 2, section A2.1.1). A summary of thicknesses previously estimated for the unit by different authors at different localities is given in table 2.1. Most previous authors appear to have relied on estimates based on outcrop width. It is not clear whether the variable

Cooper (1937)	Spring Arm 650 m
Cooper (1937)	Goose Tickle 1600 m
Stevens (1970)	Goose Tickle 305 m (but could be twice that)
Tuke (1966)	Goose Tickle 1000 m
Tuke (1968)	Pistolet Bay 500 m
Smyth (1973)	Big Springs Inlet (Hare Bay) 258 m
Schuchert and Dunbar (1934)	Table Cove 64 m (measured) 107 m (estimated)
Quinn (1985)	Bonne Bay 100 m
James and Stevens (1982)	Black Cove 75 m
Stevens (1970)	Mainland 915 - 1220 m

Table 2.1: Thicknesses estimated by previous workers for the American Tickle and Mainland formations. All localities are now interpreted as part of the American Tickle formation except the Mainland locality.

thicknesses shown in table 2.1 are a result of deformation or whether they reflect true depositional differences. However, examination of field relationships at numerous localities suggests that both factors affect the observed apparent thickness of the unit.

2.3.2.3 Lower Boundary and Character of Underlying Units

The American Tickle formation gradationally overlies the Black Cove Formation. The boundary between the Black Cove and American Tickle formations is well exposed at several localities and was placed by Stenzel et al. (1990) at a point within a transitional zone from black shale to greenish silty shale where green siltstone laminae constitute more than 30% of the rock.

2.3.2.4 Upper Boundary and Character of Overlying Units

The top of the American Tickle formation is, in most places, faulted against the overriding allochthons, with the most notable exception being in the Table Cove area where the top of the unit is simply not exposed.

Since the stratigraphic units within the allochthons are discordant with the basal thrusts, the uppermost American Tickle formation is juxtaposed against different allochthonous formations at different localities. At contacts with the Hare Bay Allochthon these include the Northwest Arm Formation (chaotic shale, limestone and sandstone) and the Maiden Point Formation (coarse feldspathic sandstone). At contacts with the Humber Arm Allochthon, they include the Blow me Down Brook Formation (coarse-grained feldspathic sandstone), the Irishtown Formation (quartzose sandstone and

shale), the Middle Arm Point Formation (variegated shale and dolostone), the Cow Head Group (variegated shale, chert, limestone, and limestone conglomerate), and the Lower Head Formation (coarse-grained lithic sandstone).

The contact zones vary in style from narrow thrust belts to the more typical wide shaly melange zones which contain clasts of local and exotic lithologies.

2.3.2.5 Daniel's Harbour Member

The Daniel's Harbour Member is a heterogeneous unit of variable distribution and thickness characterised by at least three types of limestone conglomerate and calcarenite (Stenzel et al., 1990) ranging from very thick-bedded limestone boulder conglomerate (maximum thickness 62 m; Stenzel et al., 1990) to thin-bedded calcarenite. The conglomerates and calcarenites are interbedded with siliciclastic lithologies of the American Tickle formation at different stratigraphic levels. They appear to be lensoid bodies which cannot be correlated to any great lateral extent (Stenzel et al., 1990). A detailed study of the Daniel's Harbour Member is included in Stenzel (1992).

The Daniel's Harbour Member is generally found lower than the Howe Harbour Member (see section 2.3.2.6) in any American Tickle section where both members are present.

2.3.2.6 Howe Harbour member

At the type locality at Howe Harbour (appendix 1, location map 4), the Howe Harbour member is composed of two thick beds of pebble to cobble conglomerate. The

conglomerate contains clasts of black siliceous shale, grey argillite, dark green, reddish or orange chert, light green chert, laminated fine grained limestone, dolomitic siltstone, pyrite nodules, and mafic volcanics. Clasts are subangular to rounded. They may be matrix supported, in which case the matrix consists of sandstone or silty argillite, or they may be clast supported. The maximum long diameter of the clasts is 20 cm with a mean long diameter of about 3 cm. Some clasts are platy and are aligned parallel to bedding.

Also included in the Howe Harbour member are very coarse sandstone - granule conglomerate layers 1 to 2 cm thick composed predominantly of black and green shale detritus. Towards the contact with the structurally overlying Northwest Arm Formation, these horizons become thicker, reaching a maximum thickness of 40 cm. The thin layers are normally graded, whereas the thicker layers may be trough cross laminated. All of the above lithologies are displayed at the type section for the Howe Harbour member (appendix 1, location map 4), which, however, is deformed and possibly imbricated close to the contact with the Northwest Arm Formation.

Both of the conglomerate beds exposed in the northeast area of Howe Harbour have a maximum thickness of about 40 cm, but vary laterally in thickness as the bases of the beds may have as much as 20 cm erosional relief. The thickness and number of conglomerates in the Howe Harbour member is variable and Williams and Smyth (1983) have recorded individual thicknesses of up to 10 m for the conglomerate beds. The Howe Harbour member is interbedded with silty argillite of the American Tickle formation and is restricted to localities where the American Tickle formation is structurally overlain by the Northwest Arm Formation of the Hare Bay Allochthon. The

clast types within the Howe Harbour Member resemble closely the lithologies present in the Northwest Arm Formation. At most localities the Howe Harbour Member is deformed as a result of its close proximity to the faulted contact with the Northwest Arm Formation.

The thin shale chip horizons are included with the Howe Harbour Member because they are clearly depositionally related to the conglomerate (see chapter 3, section 3.2.3).

2.3.2.7 Regional Lithological Variations

The American Tickle formation is well exposed at many localities. The most significant occurrences are considered to be those which are relatively undeformed, exhibit a complete or nearly complete section through the formation, or display specific relationships among members and/or facies (see chapter 3). Important localities in the Hare Bay/Pistolet Bay area (appendix 1, location map 4) include Shallow Bay (appendix 2, section A2.1.2), Triangle Point, Northwest Arm, Howe Harbour, Goose Tickle (appendix 2, section A2.1.1), American Tickle, and Big Springs and Little Springs inlets. At all of these localities the lithologies are similar to those found at the type section, although at Big Springs and Little Springs Inlets, the unit appears more sand rich. Smyth (1973) suggested that there is a regional southward fining of the unit and Knight (1986b) observed that the formation is finer grained in the Hare Bay area than in Pistolet Bay.

In the central part of the Northern Peninsula the most important localities are Bellburns (appendix 2, section A2.1.4) and Table Cove (section A2.1.3). At the Table

Cove and Bellburns localities sandstone in the American Tickle formation is coarser overall and constitutes a higher proportion (80%) of the whole. Sandstone is medium- to thick-bedded, medium- to coarse-grained, amalgamated, and beds vary considerably in thickness along strike. Sedimentary structures consist of partial or complete Bouma (1962) sequences. Finer grained material is interbedded with the sandstone and resembles the silty argillite which is exposed in the type area.

South from Bellburns to Bonne Bay (appendix 1, location map 3), the American Tickle Formation consists mostly of silty banded argillite with only minor sandstone beds. The Daniel's Harbour member is present at several sections in this region, but the Howe Harbour member is absent. South of Bonne Bay (appendix 1, location map 3), no detailed descriptions of the American Tickle formation are available, however workers in the area (e.g. Cawood and Williams, 1986) have given brief descriptions which suggest that lithologies are similar to the American Tickle formation farther north.

Northeast of the Port au Port Peninsula the most important locality is that at Black Cove. However, a number of localities have also been recorded inland by Schillereff (1980) which he assigned to the Black Cove Formation, but whose description clearly places them in the sandstone part of the Goose Tickle group. At the above localities the lithologies have some of the characteristics of both the American Tickle and Mainland formations. They both consist of thin- to medium-bedded medium- grained sandstone interbedded with friable recessive intervals which are siltier than the typical American Tickle formation. In places the sandstone beds contain rill markings on the upper surface. Current-aligned graptolites are also present. The Daniel's Harbour Member is

present in the American Tickle formation at Black Cove. These coarser grained lithologies in the Port au Port area may represent a lateral transition between the American Tickle and the Mainland formations.

2.3.2.8 Age of the American Tickle Formation

The American Tickle formation is characterised by a graptolite fauna. In addition, poorly preserved brachiopods have been recorded at one locality (Smyth, 1973). A complete paleontological study of the American Tickle formation has, as yet, not been carried out, but collections have been made by various workers (Stevens, 1976; Erdtmann 1971a, 1971b; Tuke 1968; Schillereff 1980) as well as the author. The specimens collected by the author were identified by S.H. Williams of Memorial University of Newfoundland. Generally the fossils indicate a middle Llanvirn age (Da 3 of the Australian scheme; see table 2.2) for the unit and forms present show closer affinities with material from other areas of North America and Australasia, rather than with material from Wales and other parts of northwest Europe (S.H. Williams, pers. comm., 1991). Tuke (1968) recorded poorly preserved specimens of Climacograptus cf. bicornis and Dicellograptus sp. from Pistolet Bay which might indicate an age younger than Llanvirn for some parts of the American Tickle formation. However, Erdtmann (1971a) has doubted at least one of the identifications of Tuke (1968), and Williams (pers. comm., 1991) has cautioned that few if any specimens collected from these units have been figured or photographed in a publication. Incorrect identification of graptolites in western Newfoundland sandstones has previously caused problems in structural and

	COW HEAD ZONES	AUSTRALIAN STAGES
Llanvirn	Llanvirn	Da3
		Da2
Arenig	U. austrodentatus	Da1
	I. v. maximus	Ya3
		Ya2
		Ya1
		Ca3
	I. v. victoriae	Ca2
	I.v. lunatus	Ca1
	D. bifidus	Ch2
		Ch1
	P. fruticosus	Be4
		Be3
	T. akharensis	Be2
		Be1
	T. approximatus	La3
	Tremadoc	La2

Table 2.2: Graptolite zonation of the Arenig and early-middle Llanvirn. Cow Head graptolite zones (Williams and Stevens, 1988; James and Stevens, 1986) shown on the left. Australian stages (Thomas, 1960; Vandenberg, 1981) are shown on the right. Abbreviations: La=Lancefieldian; Be=Bendigonian; Ch=Chewtonian; Ca=Castlemainian; Ya=Yapeen; Da=Darriwilian. Note that the position of the Arenig-Llanvirn boundary is uncertain (James and Stevens, 1986).

tectonic reconstructions (see discussions by Schillereff (1980) and Quinn (1985) of Gonzalez-Bonorino (1979)).

2.3.3 The Mainland formation

The Mainland formation is restricted to the western part of the Port au Port Peninsula. It consists of a thick package of fine-, medium- and coarse-grained sandstone and siltstone.

2.3.3.1 Lithologic Character

The Mainland formation at its type section (Crow Head/Three Rock Cove; see appendix 1, location map 1; appendix 2, section A2.2.1) consists of two main lithological types. The dominant lithology is thin- to thick-bedded fine to medium grained sandstone showing abundant partial or complete Bouma (1962) sequences (a complete Bouma sequence for a turbidite bed T is written T_{abcde}). The most common sequence is T_{bce}, with abundant parallel laminations and parting lineations. Flutes, grooves and other tool marks are common on bases of beds. Several thin beds show spectacular load casts. The sandstone is friable and has a high percentage of argillaceous matrix. Black and green shale detritus is abundant on the planes of parallel laminations.

The second lithologic type is thick- to very thick- bedded (maximum thickness 6 m) amalgamated medium- to coarse-grained massive or stratified sandstone. Dewatering structures are visible in places, and some of the beds have irregular tops. A crude parallel stratification is present in this type of sandstones which in wave-washed outcrops

shows low angle truncations (< 15 degrees). Individual sandstone beds commonly become amalgamated or pinch out along strike. Relief along the bases of amalgamation horizons may be as much as 1 m.

A less common but striking lithology is a coarse-grained trough cross-bedded medium-bedded sandstone which contains lesser amounts of muddy material than either of the lithologies described above and which is commonly associated with pinching of beds along strike.

Several rubbly horizons caused by slumping or sliding are present in the section. Thin beds of calcarenite punctuate the section at widely spaced intervals.

Recessive intervals (siltstone and shale) are present in varying proportions within the type section, but rarely do they constitute more than 50% of the whole. As the outcrop is very friable, structures in recessive intervals are hard to determine. However, where seen on wave-washed outcrops, finer grained intervals consist of parallel laminated, rippled and convoluted siltstone with minor massive mudstone.

Upward fining and thinning sequences are present at several levels in the type section but are not well developed.

2.3.3.2 Structure and Thickness

At the type section the unit is a minimum of 620 m thick with neither base nor top exposed. At the reference section (at Mainland itself, see appendix A2.2.4 for details) a 15 m thickness of Mainland formation is exposed above the Cape Cormorant Formation. The detailed structure of the Mainland formation is poorly understood, as

the formation contains few marker horizons. The type section is interpreted by Waldron and Stockmal (1991) as a relatively intact 'horse' preserved between thrust faults. This structural situation would explain why neither the base nor the top of the unit are exposed at this locality.

2.3.3.3 Lower Boundary

At the type section at Crow Head, the base of the Mainland formation is not exposed. An arbitrary base was taken at the base of the lowest completely exposed thick bed at the point of Crow Head.

South of the village of Mainland, the Mainland formation overlies limestone conglomerates of the Cape Cormorant Formation of the Table Head Group (appendix 1, location map 1). The contact between the two units was defined by Stenzel et al. (1990) as the base of the first bed of green sandstone which appears in the Cape Cormorant section.

2.3.3.4 Upper Boundary

The uppermost part of the type section which is considered to be intact is marked by a paired anticline/syncline approximately 1.5 km south of Crow Head which is shown as a major fault on the map of Stockmal and Waldron (1990). This locality does not mark the contact of the unit with any other unit, as Mainland lithologies are exposed continuously south of the folds along the coastline to Low Point (see appendix 1, location map 1). No stratigraphic contact between the Mainland formation and an overlying unit

is exposed anywhere.

Previous workers (e.g. Schillereff and Williams, 1979) have identified a section at Low Point (see appendix 1, location map 1) as the youngest exposed example of Mainland lithologies. The approximately 60 m section at Low Point is separated from the Three Rock Cove and Mainland sections by faulted and sheared shale containing 10 to 20 m thick packages of sandstone which is typically medium- to thick-bedded, coarse grained, and shows considerable evidence of soft sediment deformation. James and Stevens (1982) have reported finding graptolites from this locality which indicate a Llandeilo to early Caradoc age. The original reference which mentions these fossils (Stevens, 1976) is in error as the fossil locality is apparently somewhere in the ocean.

Offshore and apparently upsection from Low Point, is an outcrop known as the Cow Rocks (appendix 1, location map 1). This outcrop is composed of quartzites interbedded with limestone which have yielded fauna of Llandeilo age and are interpreted to be part of the Long Point Group (James and Stevens, 1982; Stockmal and Waldron, 1990).

Evidence which appeared to indicate that Low Point represents the highest exposed level in the Mainland formation (Schillereff and Williams, 1979) included:

1. The continuity of outcrop between the section from Crow Head to Low Point;
2. The presence at Low Point of graptolites of Llandeilo age (James and Stevens, 1982), which is younger than the Llanvirn age assigned to the rest of the Mainland formation;
3. The broad similarity of lithologies at Low Point with other parts of the Mainland formation;

4. The tendency of sandstone at Low Point to be cross-bedded, calcareous, and more quartzose than the rest of the Mainland formation - which, combined with 3, was interpreted to reflect a transition between the Mainland Formation and Long Point Group;

5. The similarity of strike and dip between the Low Point section and the offshore Cow Rocks (now included with the Long Point Group), suggesting a stratigraphic contact between the two units (Schillereff and Williams, 1979; H. Williams, pers. comm., 1992).

This hypothesis of stratigraphic continuity between the Mainland Formation and the Long Point Group would imply a substantial thickness (> 1.5 km) for the Mainland Formation. Problems with this hypothesis are as follows:

1. The author has documented several bedding parallel faults within the Mainland formation south of Low Point which cast doubt on any assumptions of stratigraphic continuity between the Mainland and Three Rock Cove sections and Low Point, and between Low Point and the Cow Rocks;

2. S.H. Williams (pers. comm., 1991) has pointed out that the collection of fauna from the Low Point section has never been figured in a publication, and he considers the Llandeilo age to be unsubstantiated;

3. Recent work (Stockmal and Waldron, 1990; Waldron and Stockmal, 1991) based on information from offshore seismic lines, has suggested that the platform and foreland basin sediments on the Port au Port Peninsula have been structurally incorporated into a triangle zone, and the Long Point Group has in fact been thrust over the Mainland Formation, with the thrusted contact being located somewhere between Low Point and the Cow Rocks.

Three possible interpretations for the rocks at Low Point are possible with the currently available information:

1. Faults at the base of the Low Point section have placed younger over older material, and represent smaller faults in the same sense as the main triangle zone fault postulated by Stockmal and Waldron (1990) and Waldron and Stockmal (1991). This could be the case regardless of whether the Low Point rocks are of Llanvirn or Llandeilo age;

2. The Low Point section may represent an axial succession of the same age as the rest of the Mainland Formation, which has been faulted against more marginal deposits;

3. The Low Point section may represent upper Mainland rocks whose stratigraphic position relative to the main sections is intact, and faults at the base of the Low Point section. This again could be the case for Low Point rocks of either Llanvirn or Llandeilo age.

2.3.3.5 Regional Lithological Variations

The Mainland formation as defined by the author is restricted to the west coast of the Port au Port Peninsula. However, the area of melange near Victor's Brook (appendix 1, location map 1) shown on the map of Williams (1985) has been reinterpreted by Corney (1991) and Waldron and Stockmal (1991) as a complete section through the upper part of the Table Head Group and the lower part of the Goose Tickle group, with the top of the section being marked by the base of the Humber Arm Allochthon. The sandstone part of this section has been correlated by these workers with the Mainland formation. Corney (1991) has reported conglomeratic units similar to both

the Daniel's Harbour Member and the Howe Harbour member of the American Tickle formation interbedded with the sandstone at this locality.

2.3.3.6 Age of the Mainland formation

The Mainland formation contains poorly preserved graptolites which are commonly unimodally aligned in medium or coarse sandstone. Graptolites are better preserved in fine grained horizons of the Mainland formation, but the friable nature of the exposure makes it difficult to collect complete specimens. The graptolites are indicative of a middle Llanvirn (Da 3, see table 2.2) age (S.H. Williams, pers comm 1991). Graptolites have been collected by Stevens (1976) (also reported by James and Stevens (1982)) which indicate a Llandeilo or early Caradoc age for the uppermost Mainland Formation (but see discussion above). Again these specimens have not been figured in any publication, but they have been given a GSC number. If these identifications are correct, the upper Mainland formation is the youngest part of the Goose Tickle Group exposed anywhere.

2.4 COMPARISONS BETWEEN THE MAINLAND AND AMERICAN TICKLE FORMATIONS

There are fundamental lithological differences between the American Tickle formation and the Mainland formation. Very thick-bedded sandstones, rubbly horizons, abundant cross-bedding and evidence of bioturbation are not present in the American Tickle formation, whereas the extensive laminated argillite and mudstone of the

American Tickle formation are not characteristic of the Mainland formation. However, the two units were clearly deposited in the same overall tectonic setting, and are at least partial time equivalents. Although the Mainland formation is restricted to the west coast of the Port au Port Peninsula, a gradational lateral contact with the American Tickle formation may exist northeast of the Port au Port Peninsula.

2.5. ALLOCHTHONOUS ORDOVICIAN SANDSTONES

Allochthonous Ordovician sandstone is exposed in three main areas, all in the Humber Arm Allochthon (figure 1.5). There is no equivalent allochthonous sandstone exposed in the Hare Bay Allochthon.

The name Lower Head Formation was introduced by James and Stevens (1986), for an Arenig to Llanvirn unit of medium- to coarse-grained, thick-bedded sandstone and conglomerate which overlies the Cow Head Group. James and Stevens (1986) considered the Lower Head Formation somewhat outside the scope of their study of the Cow Head Group and although they did designate a type area for the unit, they did not formally designate a type section, nor did they attempt to extend the unit beyond the area north of Bonne Bay.

Botsford (1988) undertook a revision of the stratigraphic nomenclature of the entire allochthonous sequence in the Bay of Islands area. The basic subdivision is as follows: a lower siliciclastic group (the Curling group) which would include the Summerside and Irishtown formations shown in figure 1.4; a middle carbonate group (the Northern Head group) which consists of the Cooks Brook Formation and the Middle Arm

Point Formation; and an upper siliciclastic formation (The Eagle Island formation) which is shown in figure 1.4 as the Lower Head Formation. This nomenclature has not been formally proposed, although the term Eagle Island formation has been used as if it was formal in several publications (e.g. Williams and Cawood, 1988; Cawood and Botsford, 1991). In addition, the nomenclature not been completely integrated with the regional stratigraphy; for example, the informal terms introduced by Williams et al. (1984), and Quinn (1985) have neither been dropped and incorporated into Botsford's scheme, nor have they been formally proposed.

The broad subdivision of Botsford (1988) is compatible with that for the area north of Bonne Bay (James and Stevens, 1986), although the lower siliciclastic group is not exposed north of Bonne Bay. In addition, Botsford's (1988) subdivision is consistent with the stratigraphic subdivision of the parautochthon, which is also divided into a lower siliciclastic group, a middle carbonate succession (several groups) and an upper siliciclastic group (see figure 1.3).

The upper siliciclastic formation in the Humber Arm Allochthon in the Bay of Islands area had previously been referred to the Blow me Down Brook Formation (Stevens, 1965), but Quinn (1985, 1986, 1988a) and Waldron (1984, 1985) suggested independently that the Blow me Down Brook Formation at its type section had been misinterpreted and that it is an upper Precambrian or Lower Cambrian unit. This interpretation was subsequently confirmed by Lindholm and Casey (1989) who found trace fossils indicative of an early Cambrian age, although they later revised their interpretation to include an expanded age range from Late Precambrian to Early

Cambrian (Lindholm and Casey, 1990). Botsford's (1988) map of the distribution of the Eagle Island formation does take into account the re-interpretation of Quinn (1985, 1986) and Waldron (1985), and hence the extent of the upper siliciclastic unit in the area as shown by Botsford (1988) and Quinn (1988a) is much less than had previously been thought (see, for example, Williams, 1973).

The exposures at Rocky Point and Black Point in the Port au Port area, while generally recognised as equivalents to the Lower Head and Eagle Island formations, have not been clearly designated as part of a stratigraphic unit. However, nomenclature from the Bay of Islands has generally been applied in this region (Schillereff and Williams, 1979).

Botsford (1988) has suggested that the lithological differences between his Eagle Island formation in the Bay of Islands area and the Lower Head Formation north of Bonne Bay are sufficiently great that the units merit different formation names. If this is true, the Port au Port occurrences might also merit a different name. However, for a regionally consistent stratigraphy, this would presumably require the incorporation of all three units in a single group. The author is not convinced that the lithological differences have been documented sufficiently to justify the use of two or three different formation names. It is here suggested that the term Lower Head Formation be extended to include all of its currently recognised equivalents in the Humber Arm Allochthon, with the designation of reference sections in each of the three different areas. This does not preclude the elevation of the unit to group status and subdivision into formations pending further work.

2.5.1 The Lower Head Formation - Lithologic Character

The Lower Head Formation in its type area is mainly characterised by thick- to very thick-bedded massive sandstone which is medium- to coarse-grained and poorly sorted. The sandstone commonly contains scattered granules and pebbles of argillite which nucleate spherical concretions (cannonball concretions). Fluid-escape structures such as pillars and sheet structures are also common and these also have a concretionary aspect. In some beds a crude parallel stratification is visible. Some of the thick sandstone beds are amalgamated, with patches of shale rip-up clasts and irregular scour surfaces marking the bases of depositional events. Some of the beds also have matrix-poor cross-bedded tops. Medium-bedded medium-grained calcareous sandstones showing abundant ripple drift cross-lamination are also abundant in the type area. Thin beds of fine-grained limestone are found interbedded with the sandstone as high as 250 m above the base of the unit. Minor granule to pebble conglomerate is also present. Lateral continuity of individual beds of the Lower Head Formation is difficult to evaluate but at one locality a single conglomerate bed is traceable along strike for 1 km.

2.5.2 Regional Lithologic Variations

In detail, lithologies of the Lower Head Formation vary considerably among localities. Key features of the Lower Head Formation are observed at several localities in the area north of Bonne Bay (appendix 1, location map 3). These are Martin Point North (appendix 2, section A2.3.1), Martin Point South (appendix 2, section A2.3.2), Western Brook Pond North (appendix 2, section A2.3.3), Portland Creek Hill, Portland

Creek, and St. Paul's Inlet. An extensive, although structurally complex, exposure of the unit occurs as a large raft in melange (Williams et al., 1985) in the area around Lobster Cove, north of Rocky Harbour. The Lower Head Formation at the Lobster Cove locality has been studied in detail by Gonzalez-Bonorino (1990).

The base of the Lower Head Formation is sharp, but at several localities red and green shale and limestone conglomerate, similar to lithologies of the uppermost Cow Head Group, are interbedded with sandstone for several tens of metres upsection from the lowest sandstone bed. Sandstone dykes and sills are common at the base of the Lower Head Formation, at many of the localities where it overlies red and green cherts and shales of the Green Point Formation of the Cow Head Group; e.g. at Western Brook Pond. The dominant lithology in the Lower Head Formation is thick- to very thick-bedded massive sandstone, with abundant fluid escape structures (mainly pillars). A distinctive lithology consisting of channelised conglomerate containing cobbles of limestone and chert supported by a granule sandstone matrix occurs at several localities, notably Martin Point South, the south side of St. Pauls Inlet, Lobster Cove Head, and Portland Hill. The lithologies of the conglomerate clasts resemble those in the immediately underlying Cow Head Group.

Near Portland Creek, thick-bedded sandstone is interspersed with packages of poorly exposed green shale and siltstone which are up to 25 m thick. The sandstone contains limestone granule layers up to 20 cm thick. At this locality a folded olistostromal horizon, several 10's of m thick, is also present. It contains large boulders, up to 5 m long diameter, of conglomeratic sandstone in a pebbly mudstone matrix. This

horizon is approximately along strike of the Portland Hill conglomerate locality. Other facies in the Lower Head Formation include thin- to medium-bedded, rippled, calcareous fine grained sandstone and shale, which are best exposed at Western Brook Pond.

Paleocurrent indicators are few in the Lower Head Formation, but most measurements by the author indicate flow to the south or southwest. Paleocurrent data collected by Gonzalez-Bonorino (1990) in the Lobster Cove area indicate flow to the west. Paleocurrent data for selected localities is presented in appendix 2.

Four main outcrops of the Lower Head Formation exist in the Bay of Islands area (appendix 1, location map 2). They are Middle Arm Point, North Arm Point, Eagle Island, and Black Brook North. All of these are located in the west of the area. Generally the structure of the Humber Arm Allochthon is more complex in the Bay of Islands than it is north of Bonne Bay (Cawood and Botsford, 1991). The most extensive and least structurally complex exposure of the Lower Head Formation is that at Middle Arm Point (Botsford, 1988). Here, the unit consists of medium to thick-bedded massive sandstone which is medium to coarse-grained and commonly contains spherical concretions. Thinner bedded sandstone showing ripples and rill markings is also present and is particularly well developed at North Arm Point. The lower part of the unit again contains red and green shale and numerous sandstone dykes and sills which have been referred to by Botsford (1988) as the 'slump and injection facies'. Conglomerate, consisting of dolostone fragments in a coarse sandy matrix, occurs at North Arm Point.

Two outcrops of the Lower Head Formation exist in the Port au Port region (appendix 1, location map 1); they are at Rocky Point and Black Point. The Rocky Point

section is structurally complex and consists of thick- to very thick-bedded, massive, medium- to coarse-grained sandstone, with few sedimentary structures. Flute casts are present on the bases of some beds. Interbedded within the section are some horizons of red and green shale and dolostone similar to those of the underlying Middle Arm Point Formation (Botsford 1988). The Black Point section displays a sharp, erosive contact, with 3 m of relief, between sandstone and dark shale of the Middle Arm Point Formation (Botsford, 1988). The sandstone is generally very thick-bedded, and coarse-grained to conglomeratic. Each bed contains numerous amalgamation surfaces with scour features and graded bases. Flutes up to 30 cm wide and load casts are present on the bases of some beds.

2.5.3 Structure and Thickness

The numerous exposures of the allochthonous Ordovician sandstone in the area north of Bonne Bay are interpreted to be a result of repetition across the regional strike by a series of east dipping imbricate thrust faults (Williams et al., 1985; appendix 1, location map 3). The structure of the area is considered relatively simple except for the northernmost part where some east-directed movement is inferred (Grenier 1990). Later movements in the area have thrust the Grenvillian Long Range Complex over the Humber Arm Allochthon (Grenier, 1990).

The structure in the Bay of Islands area is considered more complex than in the area north of Bonne Bay (Botsford 1988; Cawood and Botsford, 1991) with early west-directed thrusting being succeeded by easterly directed structures and an eastward

increase in the intensity of tectonism. This was succeeded by later gentle folding and vertical faulting. Cambrian sediments in this part of the allochthon have been subjected to out-of-sequence thrusting, and the entire area has been interpreted as being part of a large duplex (Lindholm and Casey, 1989). All sections in this area contain shear zones and faults, and thicknesses of units are difficult to determine.

The Black Point section is exposed as part of a large, probably emplacement-related anticline close to the base of the Humber Arm Allochthon. The Rocky Point section is structurally complex with several facing reversals, and awaits a structural re-evaluation in light of its inferred position close to a major triangle zone thrust (Stockmal and Waldron, 1990).

In all cases, the top of the Lower Head Formation is absent through faulting. However, the maximum thickness observed during the present study is about 320 m at Martin Point South (see appendix A2.3.2).

2.5.4 Lower Boundaries and Character of Underlying units

Sandstone of the Lower Head Formation overlies various formations of the Cow Head Group depending on locality. In northwesterly localities sandstone overlies mainly thick to very thick-bedded limestone conglomerate of the Shallow Bay Formation (James and Stevens, 1986). In central and eastern areas the Lower Head Formation overlies thinner bedded limestone conglomerate, shale and chert of the Green Point Formation. In the detached raft at Lobster Cove Head sandstone overlies dolostone and shale of the Lobster Cove Head Member of the Shallow Bay Formation (James et al., 1987).

In the Bay of Islands area the Lower Head Formation overlies red and green shale and dolostone of the Middle Arm Point Formation.

At Black Point sandstone overlies a 40 m thick unit of grey siltstone, which in turn overlies red and green shale of the Middle Arm Point Formation (Botsford, 1988 and unpublished data). At Rocky Point, the Lower Head Formation structurally overlies sandstone mapped by Williams (1985) as the basal melange of the Humber Arm Allochthon. This may be sandstone of the Goose Tickle group caught up in the basal melange, as shown in Waldron and Stockmal (1991).

2.5.5 Upper Boundaries and Character of Overlying Units

The stratigraphic top of the Lower Head Formation is not exposed anywhere, as it has been removed by faulting. The faulting, in most cases, is sharp, and is not characterised by melange. It juxtaposes the Lower Head Formation with stratigraphically older formations within the Humber Arm Allochthon.

The top of the Rocky Point section was previously interpreted as a rather sharp stratigraphic contact with the lowermost limestone and quartzose sandstone of the Long Point Group, hence the Lower Head Formation near Rocky Point was thought to constitute the leading edge of the Humber Arm Allochthon (Rodgers, 1965). The contact has recently been re-interpreted as a shear zone related to the development of a triangle zone thrust during the Acadian Orogeny (Stockmal and Waldron, 1990; Waldron and Stockmal).

2.5.6 Age of the Lower Head Formation

The Lower Head Formation in all areas ranges in age from late Arenig to early or middle Llanvirn (Cawood and Williams, 1986; James and Stevens, 1986; James et al., 1987; Botsford, 1988). Refer to the discussion below for more detail on this point.

2.6 AGE RELATIONSHIPS

Graptolites are the characteristic fossils which are diagnostic of age in the both the Goose Tickle group and the Lower Head Formation. Preservation is poor in the American Tickle formation because of the deformation of the unit. Preservation is also poor in the Mainland formation and the Lower Head Formation because many of the graptolites so far collected have been from coarse sandstone. The collection of biostratigraphic data has not been a priority of this study, as few workers have specialised in graptolites of this age in the North American realm, and study of the specimens would require detailed and specialised investigation of Australian correlatives (S.H. Williams, pers. comm., 1991). A brief review of paleontological information from previous workers and from the specimens collected by the author can provide some input concerning the possible diachronous westerly advance of sandstone facies into the foreland basin (Stevens, 1970; Botsford, 1988).

Workers who have collected material from the units in question include Ruedemann (1947); Tuke, 1966, 1968; Erdtmann, 1971a, b; Stevens, 1976; Gonzalez-Bonorino, 1979; Schillereff, 1980; Cawood and Williams, 1986; James and Stevens,

1986; this study.

The information provided by biostratigraphic data is as follows:

1. The Lower Head Formation is Arenig to Llanvirn in age;

2. The oldest Lower Head Formation yet found is assigned to the zone Isograptus victoriae victoriae (late Arenig). This is equivalent to the Castlemanian 2 stage of the Australian zonation scheme (see Table 2.2);

3. The youngest Lower Head Formation yet found has been assigned an age of Dariwillian 2 or 3 (latest Arenig to Llandeilo) (Cawood and Williams, 1986);

4. The age of the base of the Lower Head Formation in the area north of Bonne Bay varies slightly among different localities from I. v. maximus to U. austrodentatus zones (James and Stevens, 1986; Botsford, 1988);

5. The base of the Lower Head Formation in the Bay of Islands and at Rocky Point on the Port au Port Peninsula area is older than in the area north of Bonne Bay (I. v. victoriae) (Botsford, 1988);

6. All graptolites collected (e.g. Erdtmann, 1971a, b; this study) from the American Tickle and Mainland formations indicate a Middle Llanvirn or Darriwillian 3 age. The only exceptions to this are the collections by Tuke (1968) from somewhere in Pistolet Bay, suggesting possible Llandeilo or Caradoc ages for the American Tickle Formation, and an assemblage collected by Stevens (1976) from the top of the Mainland Formation, which also may indicate a Llandeilo or Caradoc age. No location for the collection of Tuke (1968) is available. The locations given by Stevens (1976) and James and Stevens (1982) for the Mainland collections differ, and it would seem that further study is

required to definitively establish whether the American Tickle formation or the Mainland formation or both extend into the Llandeilo or the Caradoc.

Clearly, the youngest age for the Lower Head Formation is poorly constrained, and accurate determination of the age of the base of the unit, because of its variability, also requires additional collecting and more detailed investigation. Botsford (1988) was unable, because of limited material from the Lower Head Formation, to determine whether upper zones in the Cow Head Group had been removed by erosional downcutting, or whether sandstone deposition did actually begin later at some localities. James and Stevens (1986) did infer erosion of the upper part of the Cow Head Group in places. Thus, within the Lower Head Formation there appears to be no simple east-west pattern in age of first appearance of the sandstone, and, as anticipated by Botsford (1988) there is likely to be some complication from erosional downcutting. Deposition of allochthonous sandstones in the east began from one to three zones earlier than in the parautochthonous succession which was deposited farther west. The resolution of the available data does not allow a determination of whether or not the upper parts of the Lower Head Formation and the lower American Tickle and Mainland formations were deposited coevally.

It will be shown in chapter 3 that sedimentological evidence in the American Tickle formation indicates a middle Llanvirn age for the arrival of the first slice of the Hare Bay Allochthon. Since arrival of that slice caused the cessation of sedimentation in those parts of the basin, the most likely places to look for sandstone younger than Llanvirn is in westerly areas where the American Tickle and Mainland formations do not

abut the allochthons.

An overall east - west progradation of the sandstones apparently took place if the allochthonous sandstone was deposited in the same basin as the parautochthonous succession. Gonzalez-Bonorino (1990) has stated that it was, but did not discuss his evidence. This question will be addressed in more detail in chapter 3.

2.7 SUMMARY

Two distinct parautochthonous sandstone units, the American Tickle formation and the Mainland formation, are present in the Goose Tickle Group. Only one allochthonous sandstone unit, the Lower Head Formation, has been recognised here. The Lower Head Formation is late Arenig to ?Llandeilo in age. The Mainland and American Tickle formations are at least partly time equivalent and are middle Llanvirn to ?Caradoc in age. The available information reveals no obvious progradational relationship within the Lower Head Formation, but the Lower Head Formation is at least one graptolite zone older at its base than sandstone of the Goose Tickle group.

The American Tickle formation is characterised by argillite and sandstone with a limestone conglomerate member and a polymict conglomerate member. Stenzel et al. (1990) have stated that the limestone conglomerate of the Daniel's Harbour Member contains clasts of platform sediments which underlie the American Tickle formation. The polymict conglomerate of the Howe Harbour Member is restricted to localities where the American Tickle formation is structurally overlain by the Northwest Arm Slice of the Hare Bay Allochthon, and the clasts within the conglomerate are clearly derived from

lithologies now present in the Northwest Arm formation. The Mainland formation is characterised by thin- to very thick-bedded sandstone displaying a variety of sedimentary structures.

The Lower Head Formation is a unit of medium- to very thick- bedded sandstone which is massive and relatively featureless. Conglomerate horizons in the Lower Head Formation have erosive bases, and contain clasts which are clearly derived from lithologies similar to the underlying Cow Head Group. The exact nature of the conglomerates in each unit will be addressed in chapter 3, but it is clear that in both parautochthonous and allochthonous formations at least part of the detrital content is derived from immediately adjacent units.

CHAPTER 3

FACIES AND BASIN ANALYSIS

3.1 INTRODUCTION

Facies and basin analysis were carried out with several objectives in mind:

1. To integrate the data gathered from the present study with previous work to try to refine the foreland basin model for western Newfoundland;

2. To use field relationships and facies to examine hypotheses concerning the sedimentological relationship of the Goose Tickle group and Lower Head Formation to the arrival of the Taconic allochthons.

Given the large number of units covered by this study, the wide region studied, and the unsuitability of many of the exposures for vertical measurement, detailed facies analyses were not carried out. Previous workers in the area had interpreted the Goose Tickle group (Tuke 1966, 1968; Stevens, 1970) and Lower Head Formation (James and Stevens, 1986; Gonzalez-Bonorino, 1990) as having been deposited in deep water by the actions of turbidity currents. Preliminary investigations by the author indicated that these interpretations are valid.

For the purposes of this study it was deemed most appropriate to make use of the classification of Pickering et al. (1986) to arrive at a first order interpretation of the depositional processes involved. These authors devised a classification for deep

watersediments (summarised in table 3.1) based on an original concept of Mutti and Ricci Lucchi (1972, 1974, 1975, 1978). Pickering et al. (1986) identified and subdivided facies classes based on grain size differences, internal organization and, for hemipelagic and similar sediments, composition. They then separately described and outlined the likely mode of deposition of each class and subclass. Their three tier classification is useful because it is flexible, allowing for different levels of detail depending on the type of exposure and the scope of the investigation. The classification of Pickering et al. (1986) focuses on the characteristics of each facies which are most likely to provide a key to the depositional processes involved. The classification of Pickering et al. (1986) is useful for most deep marine sediments, but does not appear to be sufficiently detailed to deal with many conglomerate deposits. In this case the facies classification of Surlyk (1984) is employed instead.

Once the processes responsible for the deposition of each facies are identified the most likely environment of deposition may be interpreted on the basis of associations of the various facies, and for these interpretations appropriate facies and basin models must be utilised (e.g. Walker, 1984; Stow and Piper, 1984; Underwood and Bachman, 1982).

In this study the American Tickle, Mainland, and Lower Head formations were subdivided into facies based on lithological information from a number of localities where vertical sections were measured, and other localities where field reconnaissance was carried out. These facies were generally (but not exclusively) interpreted using the facies classification scheme of Pickering et al. (1986). Because in several cases two separate facies recognised by the author would fall into the same category, the alphanumeric codes

Table 3.1: Facies classification of Pickering et al. (1986), with equivalent facies classifications of Walker and Mutti (1973).

A GRAVELS, MUDDY, GRAVELLY MUDS AND PEBBLY SANDS)
5% gravel (equivalent to facies A of Walker and Mutti (1973)

A1 Disorganised gravels
- **A1.1 Disorganised gravels**
- **A1.2 Disorganised muddy gravels**
- **A1.3 Disorganised gravelly muds**
- **A1.4 Disorganised pebbly sands**

A2 Organised gravels and pebbly sands
- **A2.1 Stratified gravels**
- **A2.2 Inversely graded gravels**
- **A2.3 Normally graded gravels**
- **A2.4 Graded stratified pebbly sands**
- **A2.5 Stratified pebbly sands**
- **A2.6 Inversely graded pebbly sands**
- **A2.7 Normally graded pebbly sands**
- **A2.8 Graded stratified pebbly sands**

B SANDS
> 80% sand grade, <5% pebble grade (equivalent to facies B and E of Walker and Mutti (1973))
B1 Disorganised sands
- **B1.1 Thick/medium-bedded disorganised sands**
- **B1.2 Thin-bedded coarse-grained sands**

B2 Organised sands
- **B2.1 Parallel-stratified sands**
- **B1.2 Cross-stratified sands**

C SAND-MUD COUPLETS AND MUDDY SANDS
20 - 80% sand grade, <80% mud grade (mostly silt) (equivalent to facies C and sandy parts of D of Walker and Mutti (1973))
C1 Disorganised muddy sands
- **C1.1 Poorly sorted muddy sands**
- **C1.2 Mottled muddy sands**

C2 Organised sand-mud couplets
- **C2.1 Very thick/thick-bedded sand-mud couplets**
- **C2.2 Medium-bedded sand-mud couplets**
- **C2.3 Thin-bedded sand-mud couplets**
- **C2.4 Very Thick/thick-bedded, mud-dominated sand-mud couplets**

D SILTS, SILTY MUDS AND SILT-MUD COUPLETS
>80% mud grade (of which greater than or equal to 50% is silt), <20% sand grade (equivalent to silty part of D of Walker and Mutti (1973))
- **D1.1 Structureless silts**
- **D1.2 Muddy silts**
- **D1.3 Mottled silts and muds**

D2 Organised silts, muddy silts and silt-mud couplets
- **D2.1 Graded stratified silts**
- **D2.2 Thick irregular silt and mud laminae**
- **D2.3 Thin regular silt and mud laminae**

E MUDS AND CLAYS
greater than or equal to 95% mud grade (of which <40% is silt grade). <5% sand and coarser grade (Included in G of Walker and Mutti, 1973)
E1 Disorganised muds and clays
- **E1.1 Structureless muds**
- **E1.2 Varicoloured muds**
- **E1.3 Mottled muds**

E2 Organised muds
- **E2.1 Graded muds**
- **E2.2 Laminated muds and clays**

F CHAOTIC DEPOSITS (F of Walker and Mutti, 1978)
F1 Exotic clasts
- **F1.1 Rubble**
- **F1.2 Dropstones and isolated ejecta**

F2 Contorted/disturbed strata
- **F2.1 Coherent folded/contorted strata**
- **F2.2 Dislocated, brecciated and balled strata**

G BIOGENIC OOZES, HEMIPELAGITES AND CHEMOGENIC SEDIMENTS
<5% terrigenous sand and gravel (included in G of Walker and Mutti, 1973)
G1 Biogenic oozes and arls
- **G1.1 Biogenic oozes**
- **G1.2 Muddy pelagic ooze (arl)**

G2 Hemipelagites
- **G2.1 Hemipelagite**

G3 Chemogenic sediments

of Pickering et al. (1986) are not applied directly. Appendix 2 contains a catalogue of data from selected measured sections, including for each locality: paleocurrent data; location information; and a graphic log. Other selected localities for which no section was measured are also discussed in appendix 2. Appendix 1 contains a set of maps for location of the sections measured.

This chapter provides a description of the identified facies, and a summary and evaluation of vertical and regional variations. The information is then synthesised into a basin model.

It should be noted that in general the sandstone facies described in this chapter are of similar composition viz. lithic or feldspathic arenite. Any lithologic type which does not have this composition has been described as a separate facies.

3.2 THE AMERICAN TICKLE FORMATION

The American Tickle formation contains three distinct lithological types:

1. Siltstone/mudstone/sandstone;
2. Limestone breccia and calcarenite (Daniel's Harbour Member);
3. Shale chip conglomerate (Howe Harbour member).

Each of the above can be subdivided into facies which are described separately below.

3.2.1 Mudstone/siltstone/sandstone Lithologies

The American Tickle formation is composed predominantly of silty argillite with

minor laminated mudstone and sandstone.

3.2.1.1 Facies AT1: Silty Argillite

Facies AT1 (plate 3.1) consists of massive, grey-green, non-fissile argillite beds which are from 4 to 50 cm thick with a mean thickness of about 20 cm. The estimated grain size ranges from silty mud to muddy silt. The lithology is indurated and appears massive in the field, but the bases of the beds are sharp, in some cases erosional, and in thin section normal grading is visible. Tops of beds are commonly marked by a sharp contact with a thin bedded mudstone facies (facies AT2 below). The silty argillite does not appear to be bioturbated.

The descriptive features of this facies (particularly the graded, sharp bases) are most similar to D1.2 (muddy silts) of Pickering et al. (1986) which are interpreted by these authors as having been deposited by high concentration, mud-dominated turbidity currents. Although there is no consensus on the meaning of the term 'high concentration', Middleton (1970) suggested that the boundary between high and low concentration be placed at a density of 1.1 g/cm^3.

3.2.1.2 Facies AT2: Thin- and Very Thin-Bedded Mudstone and Mudstone Laminae

Facies AT2 (plate 3.1) consists of dark grey to black indurated (non-fissile) mudstone bands up to 3 cm thick, with an average thickness of about 0.5 cm. These are found interbedded with facies AT1. The bases and tops of the mudstone layers appear sharp and there is a marked colour difference between facies AT1 and facies AT2. The

Plate 3.7: Facies HH1 (shale chip layers) of the Howe Harbour member, interbedded with silty argillite of the American Tickle formation. Northwest Arm.

Plate 3.8: Trough cross lamination in facies HH1 (shale chip layers) of the Howe Harbour member. Northwest Arm.

mudstone lacks sedimentary structures but does not appear to be bioturbated. Petrographic study shows that it is parallel laminated on a fine scale and contains scattered grains and stringers of silt. The mudstone is rich in brownish organic material which is concentrated in the laminae, and also contains small nodules of framboidal pyrite.

Although it is possible that mudstone layers might represent the waning stages of the same turbidity current which deposited the underlying silty argillite horizon, the sharp boundaries between facies AT1 and AT2 do not seem to support this hypothesis. Considered as a separate facies, the mudstone most resembles E2.2 (laminated muds and clays) of Pickering et al. (1986) which represent deposition by settling processes or by low concentration turbidity currents. The presence of the siltstone stringers suggests to the author that the latter is the case.

3.2.1.3 Facies AT3: Thin to Very Thin-bedded Sandstone

Facies AT3 (plate 3.2) consists of thin- to very thin- bedded, tan weathering sandy layers up to 5 cm thick which are interbedded with facies AT1. Grain size ranges from very fine sand to silt. The horizons are commonly laterally continuous but may also be discontinuous. They generally have sharp bases and tops, although in some cases they appear to fine vertically into massive siltstone of facies AT1. Load casts are present on some of the bases of the beds. Sedimentary structures include irregular asymmetric ripple cross-laminae and convolute laminae. These structures do not occur in any readily observable consistent sequence.

Facies AT3 does not seem to fit precisely into any of the classifications outlined by Pickering et al. (1986). The lithology is clearly sandstone which is organised rather than massive or chaotic. However, Pickering et al. (1986) described facies class B2 (organised sands) as cross-stratified or parallel-laminated whereas the structures described here are smaller in scale (cross-laminated and convolute-laminated). In addition, Pickering et al. (1986) stated that B2.1 (parallel stratified sands) are medium- to thick-bedded. Although they did not give a range of thickness for facies class B2.2, a greater thickness is probably implied than is observed for facies AT3. C2.3 (thin-bedded sand-mud couplets) is possible but the sharp tops and bases of facies 3 sandstones precludes their description, in most cases, as couplets. The grading, in some cases, of this facies into facies AT1 may indicate that C2.3 is the appropriate classification, and it is possible that in most cases the tops of the beds have been truncated. Pictorially, facies AT3 most resembles figure 30 of Pickering et al. (1986) which depicts the graded stratified silt facies, D2.1. Pickering et al. (1986) state that D2.1 overlaps in description with C2.2. Thus it is likely that the thin-bedded sandstone facies, whether classified as D2.1 or C2.2, was deposited by the actions of low concentration turbidity currents, as the vertical grain size variation and sharp bases suggest a turbidity current origin.

3.2.1.4 Facies AT4: Thin- to Thick-bedded Sandstone

Facies AT4 can be divided into two subfacies, a) and b).

Subfacies a) (plate 3.3) consists of thin- to thick-bedded, fine- to coarse-grained, resistant, tan-weathering sandstone. Maximum bed thickness is approximately 60 cm,

Plate 3.3: Facies AT4 (medium-bedded sandstone). American Tickle formation, Shallow Bay.

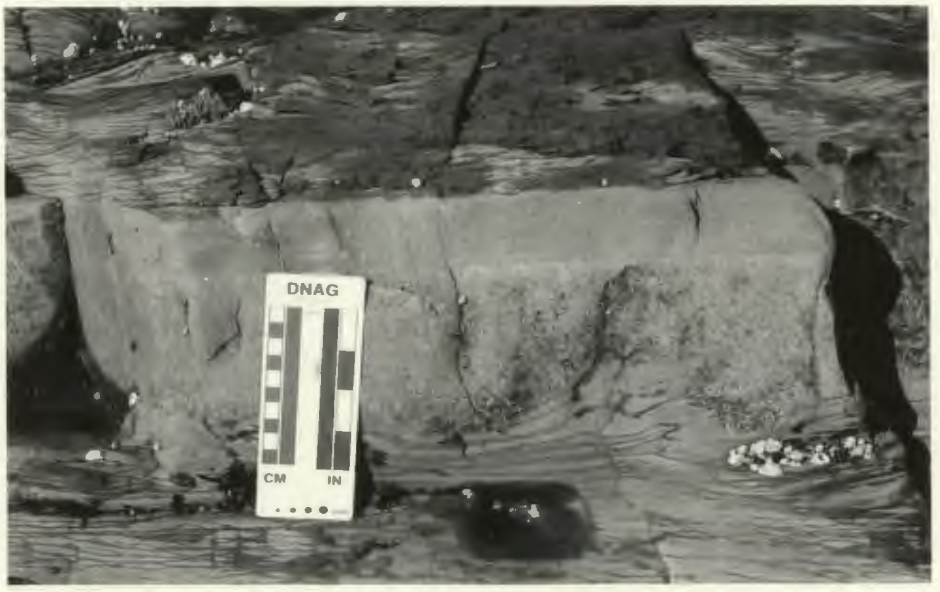


Plate 3.4: Facies AT4, subfacies b (medium to thick-bedded sandstone). American Tickle formation, Table Cove.

average thickness is 30 cm. The sandstone beds generally appear to be laterally continuous within the scale of the outcrops. In places they are slump folded and in at least one case a slumped horizon is associated with an occurrence of the Daniel's Harbour Member (see 3.2.2 below). Facies AT4 a) sandstone beds are commonly amalgamated (i.e. they display a clear erosional surface within the bed (Walker, 1968)). Each amalgamated bed shows evidence of up to three depositional events. Load casts and pseudonodules are commonly present at the bases of the beds. Flute casts are infrequently observed, as much of the exposure is almost flat lying, but they are common where the bases of beds are exposed. The flute casts are typically fairly small (3 cm maximum width), markedly pointed and elongate. These features are typical of those found on the bases of beds which begin with the Bouma (1962) division b or c (Pett and Walker, 1971). Internally the sandstones show partial Bouma sequences, of which T_{ac} or T_{bc} and T_c are the most common. Cross-lamination, ripple drift cross-lamination and convolute lamination are the most common sedimentary structures. The tops of the beds are commonly rippled with wavelengths of 15 to 50 cm and amplitudes of 2 to 3 cm.

Facies AT4, subfacies b) (plate 3.4) is best exposed in the Bellburns and Table Cove sections (appendix 1, location map 3). At these localities the sandstone beds are thicker and grain size is generally coarser. The beds show marked lateral thickness variations over distances of the order of ten metres, and commonly amalgamate along strike. Mean bed thickness is about 30 cm with a maximum thickness of about 1 m. T_{abce} and T_{ace} are the most common Bouma divisions displayed in this facies. Climbing ripple lamination is common and occurs in sets up to 30 cm thick. The climbing ripples

display a high angle of climb with both stoss and lee sides preserved. Ripples in general have a variable wavelength ranging from 3 to 10 cm and amplitudes of 1 to 3 cm. Some of the thick-bedded sandstones are cross-stratified either at their bases or above a graded interval at the base of the beds. The cross-beds are planar or tangential in sets approximately 30 cm thick, and occur in very coarse sandstone to granule conglomerate.

Unimodally aligned graptolites are abundant in Facies 4 at a few localities, notably Black Cove (Schillereff, 1980). Graptolites are less common at other localities and orientation is variable, but Tuke (1966) measured orientations of graptolites in sandstone in the Pistolet Bay area and concluded that they show an overall preferred orientation parallel to the regional paleocurrent direction (northeast-southwest).

The presence of classical Bouma (1962) sequences clearly places both subfacies in classes C2.1 and C2.2 (very thick/thick-bedded sand-mud couplets and medium-bedded sand-mud couplets) of the classification of Pickering et al. (1986). Deposition by high concentration turbidity currents is indicated. The facies classification of Pickering et al. (1986) does not directly deal with amalgamation of beds, but it is implied by those authors that the thickness of sediment deposited by each depositional event is the fundamental unit. Thus, some beds of AT4 may also represent facies class C2.3 (thin-bedded sand-mud couplets) whose mud divisions have been truncated or eroded. C2.3 beds were deposited from more dilute turbidity currents. Subfacies a) above is therefore dominated by C2.2 and C2.3 (relatively dilute), and subfacies b) is dominated by C2.1 and C2.2 (relatively higher concentration). The high rate of net deposition indicated by the high angle of climb of the climbing ripples is considered typical of deposition by

turbidity currents (Allen, 1982).

Generally speaking, dune-type cross-bedding is considered rare in turbidites. However, Allen (1970) demonstrated that under circumstances where the grain size of sediment supplied to the flow is greater than 0.025 mm, the decelerating turbidity flow may follow a path which may intersect the stability field of dunes. Experiments have shown that in fact megaripples are not developed in sediment finer than 0.1 mm (Allen, 1982). Allen (1970) therefore suggested that the classical Bouma sequence be revised to include an augmented sequence A (graded division); B_1 (lower division of parallel laminations deposited from plane beds of upper phase); C_1 (division of cross bedding); B_2 (intermediate division of parallel laminations deposited from plane beds of lower phase); C_2 (division of cross lamination); D (upper division of parallel laminations); E (mud division). The occurrence of cross-bedding in the coarse grained parts of facies AT4, subfacies b) of the American Tickle formation is entirely compatible with the model produced by Allen (1970) and relates to the coarse grained nature of the sediment supply. The most common sequence in which this cross-bedding is therefore found is AC_1C_2 and $AB_1C_1C_2$.

The preferred orientation of the graptolites found in facies AT4 suggests that they were likely transported into the area by turbidity currents as suggested by Tuke (1966).

3.2.1.5 Regional Considerations

At most localities facies AT1 is the predominant facies, constituting an estimated

70 - 95 percent of the exposures, except for the Bellburns area where it constitutes 10 - 20 percent. Facies AT1 normally contains interbeds of facies AT2 which, however, still constitute less than 10 percent of any exposure. Facies AT1 contains interbeds of facies AT3 at only a few localities and facies AT3 also constitutes less than 10 percent of any exposure. Facies AT4 is not present at all localities, but normally makes up 10 to 30 percent of an exposure except in the Bellburns area where it is the predominant facies. In other words, the American Tickle formation throughout most of its lateral extent is dominated by facies class D (of Pickering et al., 1986), with varying proportions of C and small but constant proportions of E, except in the Bellburns area where class C is dominant and in the Black Cove area where there are roughly equal proportions of C and E (Schillereff, 1980).

Minor thin- to medium-bedded fine-grained limestone occurs in the exposures at Big Springs Inlet and at Croque. The limestone is featureless and micritic, most resembling pelagic slope limestone. It occurs in the most easterly exposures of the American Tickle formation and its presence may indicate a shallowing trend towards the eastern margin of the basin. Tuke (1966) also mentioned thin-bedded fine-grained limestones which he described as being characteristic of the middle part of the section but he did not describe at which localities he observed them.

Only one possible trace fossil was observed by the author in float. Otherwise trace fossils were not observed in the unit at any locality nor have they been reported by any other author, and banding in the fine grained facies is apparently undisturbed by burrowing organisms. It is therefore suggested that anoxic conditions prevailed

throughout the region.

Paleocurrents in the American Tickle formation as measured by the author are predominantly directed towards the south (see appendix 2). Previous workers (Knight, 1986a,b; Williams and Smyth, 1983; Smyth, 1973; Tuke, 1966) have also reported paleocurrent directions predominantly to the south, but some directions to the west have been recorded (Williams and Smyth 1983; Smyth 1973) at American Tickle. At Big and Little Springs Inlet, Smyth (1973) recorded northeasterly directions from flute casts. Plate 3.5 shows probable cross sections of flute casts at Little Springs Inlet which have clearly been affected by the strong cleavage in the area, and paleocurrent directions obtained from these features should be treated with some caution. At Little Springs Inlet the author recorded a bimodal distribution of paleocurrent directions (from ripples) to the northeast and southwest, and at Big Springs Inlet the mean direction is to the southeast. The exposures at Little and Big Springs Inlets represent some of the easternmost and hence most deformed examples of the American Tickle formation. However, the possibility cannot be ruled out that a real variation in paleocurrent direction exists at these most easterly localities.

The American Tickle formation is clearly coarser than the underlying Black Cove Formation and in that sense a coarsening upwards sequence is present in the foreland basin succession. However, within the American Tickle formation, there is no noticeable coarsening or thickening upward sequence. In fact, in the composite section constructed by Tuke (1966), the resistant sandstone facies (facies AT4) is more abundant at the base of the unit, implying an overall fining upward within the American Tickle formation.

Plate 3.5: Cross sections of deformed flute casts. American Tickle formation, Little Springs Inlet.

Plate 3.6: Clast of American Tickle Formation sandstone in limestone conglomerate of the Daniel's Harbour Member. Daniel's Harbour.

The measured section provided in this study for Goose Tickle appears to corroborate this impression (see appendix 2, section A2.1.1). Fining upward sequences appear to be present at localities other than the type section, but in many cases it difficult be sure if this relationship truly exists or whether it has been obscured by poor exposure or deformation. At some localities facies AT4 occurs as apparently randomly distributed single beds or bundles interbedded with the dominant facies AT1. Bundles of sandstones are not necessarily present at the top of the unit (see measured sections in appendix 2 for typical facies distributions) where it abuts the Hare Bay or Humber Arm allochthons.

3.2.2 Daniel's Harbour Member

The Daniel's Harbour Member is treated only briefly here as it is the subject of a separate study (Stenzel et al., 1990). The Daniel's Harbour Member (plate 3.6) is a unit which is highly variable, ranging from very thick-bedded coarse-grained limestone conglomerate to thin-bedded calcarenite. In places a conglomerate horizon may be overlain by one or two beds of calcarenite, whereas at other localities calcarenite occurs separately. The most common lithology in the Daniel's Harbour Member is massive, light grey, matrix-poor limestone conglomerate with a maximum bed thickness of 40 m. This lithology is typical of the type section at Daniel's Harbour (appendix 1, location map 3) and localities south of the type section (Stenzel et al., 1990). Clasts in this type of conglomerate are commonly disposed in an interlocking texture. North of Table Cove (appendix 1, location map 3), a common lithology of the Daniel's Harbour Member is a matrix rich dark grey conglomerate with a maximum bed thickness of 62 m. (Stenzel

et al., 1990). Clasts in the conglomerate, which are angular to subangular, are mostly composed of shallow water limestones characteristic of the Table Head Group. Lithologies typical of the American Tickle formation appear as clasts in both types of conglomerates (plate 3.6), and as matrix in the matrix rich variety (Stenzel et al., 1990). Calcarenite beds range in thickness from 5 cm to 3 m (Stenzel et al., 1990) and display Bouma sequences. In at least one locality, the Daniel's Harbour Member is associated with slump folding in facies AT4 of the American Tickle formation.

The Daniel's Harbour Member has been interpreted as having been deposited by debris flows (conglomerate facies) and turbidity currents (calcarenite facies) (Stenzel, pers. comm. 1988; Stenzel et al. 1990). The inferred direction of transport of the Daniel's Harbour sediments was to the north and west. (Stenzel et al., 1990). A detailed study of the Daniel's Harbour Member is included in Stenzel (1992).

3.2.3 Howe Harbour member

The Howe Harbour member includes numerous beds of shale chip sandstone and conglomerate which are situated near the top of the American Tickle formation where it abuts the Northwest Arm Formation. Two distinct facies are present.

3.2.3.1 Facies HH1: Shale Chip Layers

Facies HH1 consists of very thin-bedded coarse sand to granule layers which are composed predominantly of black and green shale chips (plate 3.7). The shale chips are aligned parallel to bedding and sorting is variable. These horizons, where present, may

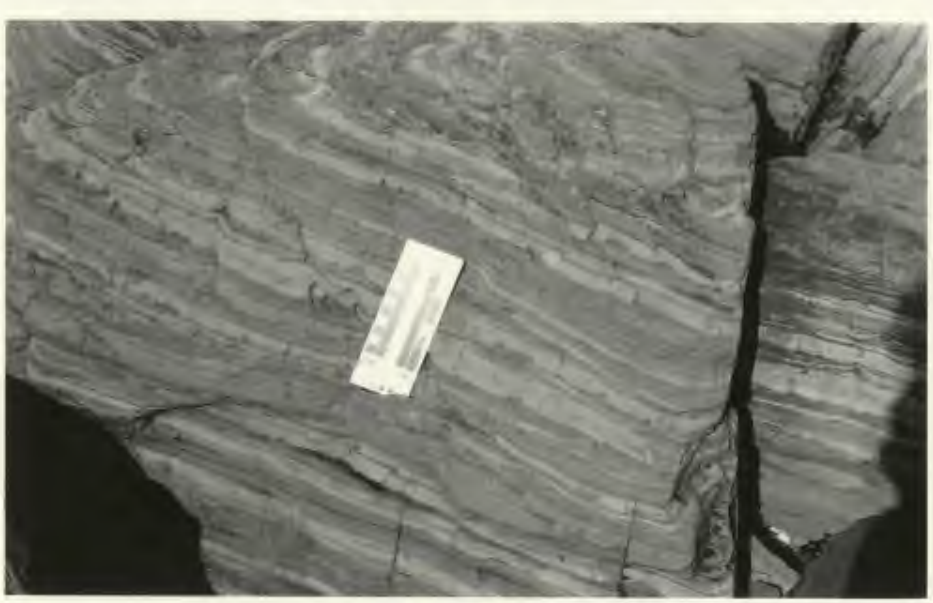


Plate 3.7: Facies HH1 (shale chip layers) of the Howe Harbour member, interbedded with silty argillite of the American Tickle formation. Northwest Arm.

Plate 3.8: Trough cross lamination in facies HH1 (shale chip layers) of the Howe Harbour member. Northwest Arm.

thicken upsection, reaching a maximum thickness of 30-40 cm. At these greater thicknesses they are not noticeably graded but may display trough cross-lamination (plate 3.8). The shale chip layers are unusual in that they are very coarse in relation to their thickness, are clast supported, and are composed almost entirely of flat shale clasts varying from coarse sand size to pebble size. Thus it is not surprising that they are difficult to classify using the scheme of Pickering et al. (1986). However, depending on grain size, they might be described as class A1.1 (disorganised gravels, muddy gravels, gravelly muds, and pebbly sands) or B1.2 (thin-bedded coarse-grained sands).

A1.1 could result either from high concentration turbidity currents, debris flows, or winnowing by bottom currents, whereas B1.2 is interpreted as having been deposited under traction processes, possibly through winnowing by strong bottom currents (Pickering et al. 1986). The composition and clast size of the shale chip layers is considerably different from the rest of the American Tickle formation, and reworking of the typical American Tickle detritus by bottom currents is unlikely to have produced this facies. The lack of matrix suggests that they are unlikely to be debris flows and so they were probably deposited by high concentration turbidity currents.

3.2.3.2 Facies HH2: Conglomerate

Conglomerate in the Howe Harbour member contains clasts of black siliceous shale, grey argillite, dark green, reddish or orange chert, light green chert, laminated fine grained limestone, dolomitic siltstone, pyrite nodules and mafic volcanics (plate 3.9). This represents a greater variety of clasts than found in facies HH1, but the black and

Plate 3.9: Facies HH2 (conglomerate) of the Howe Harbour member. Howe Harbour.

green shale/siliceous shale component and grey argillite are similar to clasts within the shale chip conglomerate of HH1. Clasts in facies HH2 are subangular to well rounded. They are set in a matrix of sandstone or silty argillite and may be matrix or clast supported, but are most commonly clast supported. The maximum long diameter of the clasts is 20 cm with a mean long diameter of 3 cm. The conglomerate occurs in lensoid beds, generally less than 1 m thick, with irregular bases. They may contain thin interbeds of shale indicating that more than one depositional event has contributed to some of the beds. Clasts are generally aligned parallel to bedding, but may also be at a high angle to it.

The poor sorting, irregular bases, characteristic thickness and clast support would seem to place the Howe Harbour member conglomerates in facies class A1.1 (disorganised gravels) of Pickering et al. (1986). The most likely mode of depositionwould be as a debris flow or high concentration turbidity current, with winnowing by bottom currents seeming unlikely for the reasons outlined in the previous section. Where the matrix content is higher, the facies more closely resembles facies A1.4 (disorganised pebbly sands), which are deposited by high concentration turbidity currents, and in fact Pickering et al. (1986) document the close association of classes A1.1 and A1.4. Pickering et al. (1986) describe examples of facies A1.1 with thin to very thin beds or stringers of gravel which may be as little as one pebble thick. The rounding of the clasts suggests that they were ultimately derived from subaerial piles of unconsolidated sediments. The close association of facies HH1 and HH2 within a vertical section, their compositional similarity, and the apparent genetic relationship between the

two facies classes represented, all support a close depositional relationship between the two facies.

3.2.3.3 Relationship to Northwest Arm Formation

The Northwest Arm Formation is structurally the lowermost unit of the Hare Bay Allochthon, and is composed of chaotic black and green shale which contains rafts of limestone, sandstone and minor volcanic and plutonic rocks. Although the unit is chaotic, many of the clasts have the appearance of dismembered beds and display a ghost stratigraphy. Tuke (1966) measured paleocurrents between dismembered fragments of similar lithology and found them to be consistent. Tuke (1966, 1968) and Knight (1986a) have identified a phase of isoclinal folding in the unit which is earlier than the Taconic deformation that is usually related to emplacement of the allochthon. This early phase of folding represents early deformation related to the movement of the unit as an olistostrome, with Taconic deformation overprinting the early folds.

The Howe Harbour member only occurs in the American Tickle formation where it abuts the Northwest Arm Formation. The shale chip facies (HH1) generally appears lower in the section than the conglomerate (HH2) facies of the Howe Harbour member and both are commonly (although not always) within 50 m (vertical thickness) of the contact with the Northwest Arm Formation. Lithologies of clasts in the conglomeratic facies of the Howe Harbour member are identical to those in the Northwest Arm Formation, and the Northwest Arm Formation contains conglomeratic horizons which are similar to those of the Howe Harbour member. It is clear that depositionally and

compositionally the Howe Harbour member and the Northwest Arm Formation are very closely related.

3.2.4 Overall Interpretation

It is now appropriate to construct a qualitative model of the basin in which the American Tickle formation was deposited. Overall, the unit is composed of predominantly fine grained sediments deposited in deep water (below wave base) under anoxic conditions. Stow and Piper (1984) have outlined a number of idealised facies associations which can occur in fine grained sediments. The common association of silt and sand (AT1, AT4, and minor AT2) in the American Tickle formation as a whole most resembles their 'silty-sandy distal lobes' or in places the association of silt and mud only (AT1, AT2, AT3) resembles 'distal silt-mud lobes'. For most of the American Tickle formation, the lateral continuity of beds suggests that deposition probably did not occur in channels. In the Bellburns area, the lack of lateral continuity of sandstone beds may indicate deposition of sands in small shallow channels incised into the basin floor in a setting which was closer to a source of sediment. The American Tickle formation might therefore be interpreted as the product of deposition by turbidity currents on the outer fan area of a submarine fan or fans. The paleocurrent data indicate that the outer lobes of these 'fans' were elongate in response to the narrow, elongate shape of the basin, and that the regional axis of the basin sloped in a southerly direction.

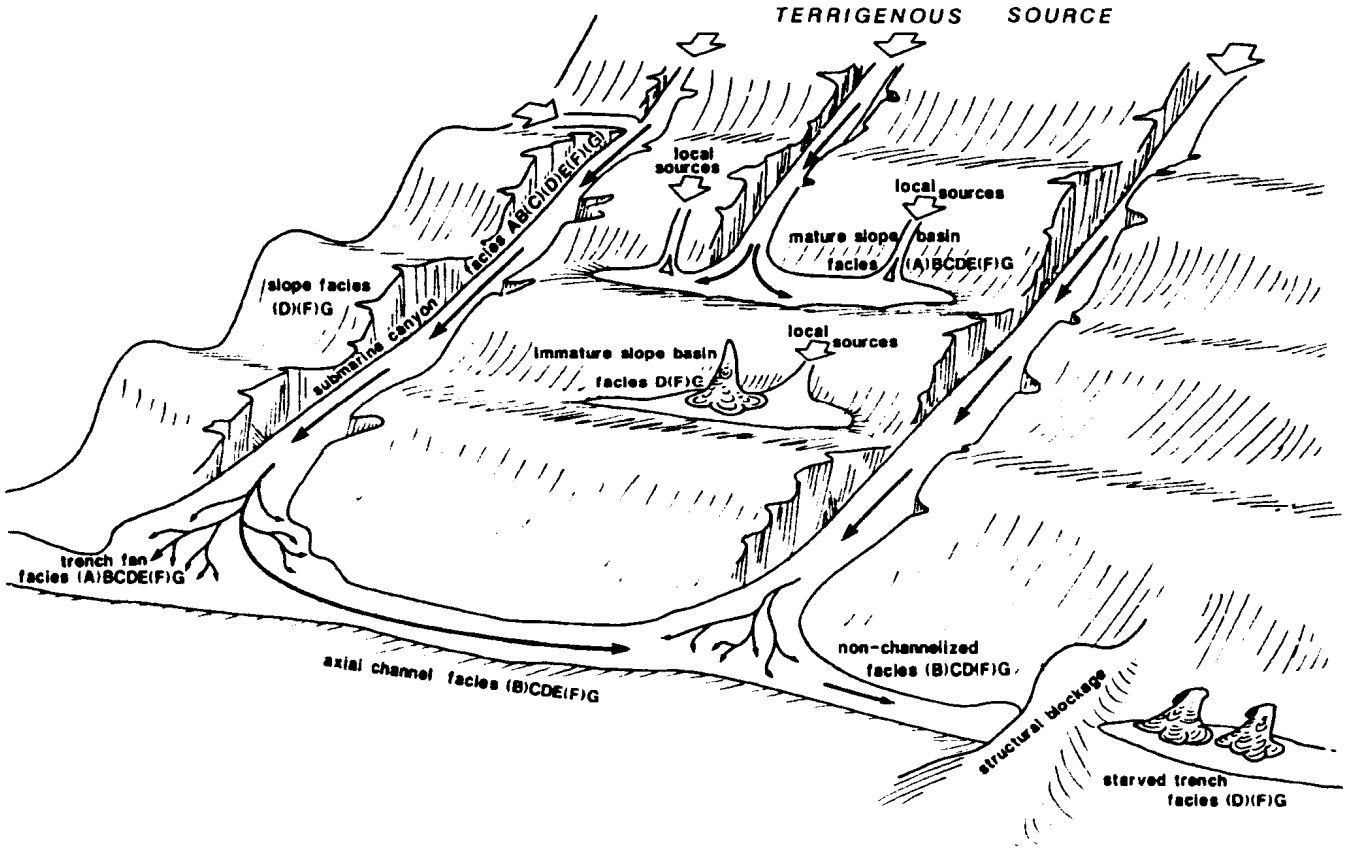
The use of the term 'lobe' implies deposition on a submarine fan, and at this point it is appropriate to discuss the problem of referring to deposits as 'fans' when a fan-

shaped geometry cannot be documented. Hiscott et al. (1986) have commented on the inappropriateness of using the fan model in cases where a) the shape of the depositional system is not known, b) it is not known whether there were one or more feeder channels and c) paleoflow is consistently along the axis of the basin. All of these criteria apply to the American Tickle formation. Hiscott et al. (1986) suggest that if the term fan is to be used then it should be specified the system was 'grossly oversupplied' and that the deposit shape was determined by basin shape.

The foreland basin in which the American Tickle formation was deposited was not a trench, sensu stricto, as it was constructed on continental rather than oceanic crust (see, for example, Quinlan and Beaumont, 1984). However, patterns of deposition may still be understood in terms of a trench model, such as that outlined by Underwood and Bachman (1982) and Bachman (1982), as the overall geometry and other tectonic features are similar. Underwood and Bachman (1982) and Bachman (1982) again emphasised that the elongate geometry of trenches renders it inappropriate in most cases to interpret facies associations using the deep sea fan model. Instead, Underwood and Bachman (1982) adopted a 'convergent margin facies model' basing their facies classification on publications by Walker and Mutti (1973) and Ricci Lucchi (1975). This model is summarised in figure 3.1. Facies classes shown in the Underwood and Bachman (1982) model are broadly similar to those of Pickering et al. (1986) (see table 3.1 for equivalencies).

Applying the model of Underwood and Bachman (1982) to the American Tickle formation, the predominance of facies D with lesser proportions of C and E, the axially

Figure 3.1: The facies associations of the Goose Tickle group and Lower Head Formation can be explained using the combined convergent margin facies model of Underwood and Bachman (1982). Equivalents to these in the classification of Pickering et al. (1986) can be found in table 3.1. The setting inferred for the American Tickle formation is the non-channelised trench floor. The setting inferred for the Lower Head Formation is a trench slope basin or basins (satellite basin).


TERRIGENOUS SOURCE
local sources
local sources
mature slope facies
basin (A)BCDE(F)G
slope facies (D)(F)G
facies AB(C)(D)E(F)(G)
submarine canyon
local sources
immature slope basin facies D(F)G
trench fan facies (A)BCDE(F)G
axial channel facies (B)CDE(F)G
non-channelized facies (B)CD(F)G
structural blockage
starved trench facies (D)(F)G

directed paleocurrents, combined with the lack of obvious thinning and fining upward sequences, most resemble a non-channelised trench floor with facies associations characteristic of outer 'fan' to basin plain. Underwood and Bachman (1982) state that the most common way of transporting sediment into the trench is via large submarine canyons which cross the trench slope. In the American Tickle formation it cannot be demonstrated directly that entry of sediment was through submarine canyons, since the canyons themselves are not preserved. Evidence for submarine canyon supply may exist in the form of the ubiquitous black and green shale detritus present in the American Tickle Formation. If this shale was derived from internal rip-ups, it would presumably be associated with sandstone and siltstone clasts, which it is not. Instead, the shale chips were probably derived from the previous continental margin basin floor subsequently uplifted to comprise the eastern foreland basin slope. The persistence of this type of detritus implies substantial erosion of the slope, and thus suggests that the shale chips may have been derived directly from canyon walls. The sand/mud ratio of the trench floor deposits may be dependent on the proximity of the site of deposition to a submarine canyon (Underwood and Bachman, 1982). The regional variations in sand/mud ratio in the American Tickle formation might thus be interpreted as being related to the proximity of a sediment input point.

At least three sediment input points, located to the east of the present eastern limit of exposure of the formation, are required to account for the pattern of sedimentation observed in the American Tickle formation. The easterly location of the input points is suggested by the ubiquitous black and green shale detritus in the American Tickle

formation.

To account for the presence of the American Tickle sediments in Pistolet Bay and Hare Bay, the first sediment input point would have to be located somewhere northeast of Pistolet Bay. The second would be somewhere northeast of but relatively closer to the Bellburns area to account for the greater sand/mud ratio and higher degree of channelisation in that area, and a third might exist somewhere north of Black Cove to account for the high sand content of the Mainland formation (see discussion of the Mainland formation). The area between Bonne Bay and the Port au Port Peninsula is poorly exposed and understood, and it is possible that another sediment input point could have existed in that vicinity.

Underwood and Bachman (1982) also noted the importance of the location of the canyon head with respect to sea level. If the canyons head in the slope, and sea level is high, then the basin will not receive detritus from the shelf. If on, the other hand, the canyons either head in the shelf, or sea level is low, or both, then the basin will receive terrigenous detritus from the shelf. It will be demonstrated in chapter six that the lithologies of the American Tickle formation do contain detritus which is clearly exotic to the foreland basin and its trench slope, thus either the main submarine canyons were headed on the shelf, or sea level was low. The sea-level curves of Fortey (1984) for the Ordovician suggest that sea-level reached a high during the middle Llanvirn, and the overall sand-poor nature of the American Tickle formation would indicate a relatively high sea level. If this is true, the submarine canyons most likely headed in the shelf.

Bidirectional transport along the trench floor is predicted by the model of

Underwood and Bachman (1982). In the case of the American Tickle formation, unimodal southwesterly paleocurrent directions are prevalent. However, it should be noted that information is sparse from areas north of all of the proposed sediment input points.

Hiscott et al. (1986) have suggested that the foreland basin in Quebec, during the deposition of the Caradocian Cloridorme Formation, was characterised by a flat basin floor which would allow for the flow of megaturbidity currents in either direction along the axial regions of the basin, but that the basin was segmented by intrabasinal highs which generated flow reflections and deflections.

The American Tickle formation differs from the Cloridorme Formation in Quebec in that no occurrences of large scale megaturbidites have been observed, nor have instances of reflection of turbidity currents been observed. Thus there is no evidence in the American Tickle Basin for the axial highs reported by Hiscott et al. (1986) in the Cloridorme basin. The only variation in paleocurrent directions is in the most easterly exposures of the American Tickle formation which, if not caused by deformation, could reflect deposition by unconfined turbidity currents nearer the eastern margin of the basin on the 'trench fan' of Underwood and Bachman (1982).

The Daniel's Harbour Member was interpreted by Stenzel et al. (1990) as having been deposited by easterly derived debris flows and turbidity currents derived from uplift of platform and foreland basin clastics along shallow thrust faults in front of advancing allochthons. The interpretation for the Howe Harbour member (Quinn, 1991) is similar but not identical. Both the Howe Harbour member (Quinn, 1991) and the Daniel's

Harbour Member (Stenzel et al., 1990) were transported down a slope which lay to the east or southeast of the foreland basin. The Howe Harbour member was likely also derived from uplift along faults (either thrust or normal faults) in front of advancing allochthons, but it appears higher in the American Tickle formation than the Daniel's Harbour Member, and was generated by uplift of older passive margin slope sediments rather than platform and early foreland basin sediments. Thus the faulting which generated the Howe Harbour member was probably deeper seated, located farther east, and was active slightly later than that which generated the Daniel's Harbour Member. This might be explained by a structural model which involves compression over a period of time, and generation of an imbricate thrust package. The Daniel's Harbour Member may have been generated by shallow thrusting at the westward periphery of the system, whereas the Howe Harbour Member was generated by faulting in the main area of compression.

Underwood and Bachman (1982) noted that sediment may be supplied to the trench floor from secondary sources consisting of background settling of hemipelagic debris and locally derived mass flows including slumps and slides. High porewater pressures resulting from tectonically induced dewatering at the base of the eastern slope of the foreland basin, combined in some cases with oversteepened slopes, provides a mechanism for recurrent slope failure which may have resulted in the debris flows and high concentration turbidity currents of the Howe Harbour member.

There is abundant evidence for the existence of a slope during the deposition of the American Tickle formation. Early folding in the Northwest Arm Formation has

already been discussed, and Knight (1986a) has also found early recumbent folding within the American Tickle formation itself. It has been demonstrated that deposition of the high concentration turbidites of the Howe Harbour member was closely related to the emplacement of the Northwest Arm Formation, which was itself emplaced by gravity sliding (Tuke, 1968; Quinn, 1991). Tuke (1966) had previously suggested that fluids at the base of a slope generated slumping and resulted in final movement of the Northwest Arm Formation.

Simple slumping of slope sediments is not sufficient to explain the characteristics of the Howe Harbour member and the Northwest Arm Formation, because both contain extrabasinal clasts of volcanic and plutonic rocks. In addition, the presence of chert clasts as well as shale fragments, and the rounding of the limestone clasts indicates at least partial lithification of the supplied slope sediments. This implies supply of exotic materials which were previously exposed subaerially on a fault scarp. They may have later been drowned during sea-level rise and become incorporated in gravity flows or they may have been directly derived from a fan-delta source. Despite these complexities, it is clear that the coarsening and thickening upwards Howe Harbour member records the arrival of at least the first slices of the Hare Bay Allochthon.

It has been shown that there is little evidence of an overall coarsening upwards in the dominant sandstone/siltstone lithologies of the American Tickle formation, yet Cawood et al. (1988) have cited a coarsening upward sequence at the Black Cove section as evidence of westward migration of the depocentre of the foreland basin, and the imminent arrival of the Humber Arm Allochthon. Stouge (1986) has also referred to

coarsening upwards within the American Tickle formation. If any vertical variation is visible in the American Tickle formation, it is a fining upwards sequence, and since the formation is truncated by the Humber Arm and Hare Bay allochthons at different levels, the sandstones at Black Cove may simply be a truncated bundle fortuitously juxtaposed against the contact with the Humber Arm Allochthon. There is little in the regional facies distribution or paleocurrent data from the siltstone/sandstone lithologies of the American Tickle formation to support the concept of a simple relationship between the sandstones of the American Tickle formation and the advancing allochthons.

There is also no evidence within the American Tickle formation for a gradual westward progradation of sediment into the basin. This is not surprising since the inferred width of the axial region of the basin was narrow (Bradley, 1989), as is the preserved width of outcrop. In order to infer a westward progradation for sediment into the basin, one must thus consider evidence from the allochthons which would presumably record a history of the more easterly part of the foreland basin. However, before this can be done, the question must be addressed as to whether sandstones previously identified as being deposited in a broadly similar tectonic setting in the allochthons (e.g. Stevens, 1970; Quinn, 1988a, category 2b; Gonzalez-Bonorino, 1990) were deposited in the foreland basin proper or whether they were deposited in a trench slope basin.

The general pattern reflected by the American Tickle formation is one of subsidence prior to deposition, as the formation is underlain by the deep water limestone of the Table Cove Formation and deep water shale of the Black Cove Formation (Stenzel et al., 1990). The interval of subsidence was succeeded by the gradual influx of a

generally fining upward succession of silty/sandy siliciclastic material. Imminent emplacement of the Northwest Arm Formation as a result of thrusting along the eastern margin of the basin generated localised deposition of the Howe Harbour member, which was followed by a cessation of siliciclastic sedimentation in those areas.

3.3 THE MAINLAND FORMATION

The Mainland formation is restricted to the west coast of the Port au Port Peninsula and contains a much higher proportion of sand than the American Tickle formation. A number of different facies may be recognised.

3.3.1 Facies ML1: Thin to Medium-bedded Sandstone

Facies ML1 consists of thin- to thick-bedded fine- to medium-grained sandstone (plate 3.10) showing partial or complete Bouma (1962) sequences. The most common sequence is T_{bce} with abundant parallel laminations and parting lineations. Flutes are common on bases of beds as are grooves and other tool marks. Several thin beds show spectacular load casts. The sandstone is friable and appears to have a high percentage of mud. Black and green shale detritus is abundant on the planes of parallel laminations. The beds are laterally continuous and do not vary in thickness. They are separated by thin- to medium-bedded recessive silty intervals.

The facies ML1 lithology with its well developed Bouma (1962) sequences can be classified as facies C2.2 (medium-bedded sand-mud couplets) and C2.3 (thin-bedded sand-mud couplets) using the classification scheme of Pickering et al. (1986). All were

Plate 3.10: Facies ML1 (thin- to medium-bedded sandstone). Three Rock Cove.

Plate 3.11: Low angle truncations in sandstone of the Mainland formation (facies ML1 and ML2). Mainland.

deposited by low concentration turbidity currents. A notable difference between thesebeds and similar facies (facies AT4) in the American Tickle formation is the relative frequency of parallel lamination and the infrequency of ripple drift cross-lamination.

A number of fine-grained thick-bedded parallel-laminated sandstones occur as isolated beds throughout the section. These beds seem to be most similar to facies C2.2 (medium-bedded sand-mud couplets), however they are unusual in that they are fine-grained in comparison to their thickness, grading is not well developed, and they are dominated by the b division of the Bouma sequence. The parallel lamination is completely regular and so despite the fact that they are thick-bedded, they are not included with facies ML2 below. They do not resemble facies B2.1 (parallel stratified sands) in that the internal stratification is not similar to that described by Pickering et al. (1986). They are most likely related to the dominant ML1 lithologies, belong to facies class C2.2, and were deposited by moderate concentration turbidity currents.

3.3.2 Facies ML2: Thick-bedded to Very Thick-bedded Sandstone

Facies ML2 consists of thick-bedded to very thick-bedded sandstone (maximum thickness 6 m) which ranges in grain size from medium- to coarse-grained. The beds range from massive near the bases to parallel laminated near the tops, with a rather poorly developed normal distribution grading. On closer examination some of the 'parallel' lamination shows very low angle truncations similar to those described by Mutti and Ricci Lucchi (1978) (plate 3.11). The tops of the beds appear to be gradational with overlying fine-grained silty horizons which may show ripple cross-lamination.

Laminations in the sandy upper parts of the thick beds have a wavy appearance. This indicates that the tops of the beds have been deformed, possibly as a result of partial liquefaction or variable fluid pressure. A second possibility is that the occurrence of these features at the top of the bed may represent a transition into the field of climbing ripples with a very high angle of climb.

ML2 thick beds are commonly amalgamated, with relief on amalgamation horizons greater than 1 m in some cases (plate 3.12). Amalgamation horizons are commonly marked by shale or siltstone chips which are probably rip-up clasts. Large 20 cm wide flute casts are common on the bases of the beds, and occasional longitudinal ridges (Dzulinski and Walton, 1968) are observed. Calcite cemented 'cannonball' concretions are observed in some of these beds, and in places unimodally aligned graptolites are preserved on the surface of the concretion parallel to bedding. It has been suggested by S.H. Williams (pers. comm. 1991) that this phenomenon is caused by lack of available oxygen to oxidise the graptolites, as a result of early incorporation of oxygen into the calcium carbonate cement. Hiscott (1977) has cited evidence for formation of cannonball concretions during the early stages of diagenesis, and has suggested that the concretion forming process may in fact be enhanced by the presence of organic material.

Facies ML2 belongs to facies class C2.1 (very thick/thick-bedded sand-mud couplets) of Pickering et al. (1986). Deposition of this facies occurred from high concentration turbidity currents. This facies is not present at any locality within the American Tickle formation.

Plate 3.12: Facies ML2 (thick- to very thick-bedded sandstone). Note deeply scoured base of topmost bed. Three Rock Cove.

Plate 3.13: Facies ML3 (cross-bedded sandstone) subfacies b. Low Point.

3.3.3 Facies ML3: Cross Bedded Sandstone

Facies ML3 consists of medium to very thick beds which contain cross-bedding. Within cross-bedded sets the sediment is very coarse-grained, contains less muddy matrix than all of the facies described above and is better sorted. If a bed within this facies is completely composed of cross-bedded sandstone, it commonly has a sharp base and top and in places dune-like bedforms are clearly developed on the tops of the cross-bedded horizons. These bedforms may be overlain by finer grained material which appears to have settled over them. The cross-sets vary in morphology from tabular to trough, and from high to low angle.

Two possible subfacies have been identified:

Subfacies a) In this subfacies the cross-bedded lithology is clearly coarser than the surrounding sediment and is associated with dune or megaripple forms overlain by finer grained sediment within the same bed. The cross-sets or dune forms are rarely greater than 30 cm thick. These beds tend to show a considerable lateral variation in thickness, and may pinch out laterally across strike within approximately 10 metres. (Note that strike is considered to be approximately perpendicular to the regional paleocurrent direction). The basal contacts of the cross-sets are predominantly sharp and flat but may be slightly erosive in places;

Subfacies b) Examples of this subfacies are distinguished mainly by the thickness of the cross-sets which can be as great as 1 m (plate 3.13). This type of cross-bedding is characterised by scoured bases within graded beds. The base of the cross-set may be 5 - 10 cm from the base of the bed. Shale chips may be distributed along the foreset of the

cross-bed.

Both subfacies a) and b) appear to belong to facies B2.2 (cross-stratified sand), although subfacies b) is unusual in terms of the thickness of the sets and the degree of scouring with which they are associated. Facies class B2.2 is interpreted by Pickering et al. (1986) as having been deposited by reworking of sands through tractional processes beneath dilute turbidity currents or strong bottom currents.

It should be noted that subfacies a) and b) are considered different from the upper parts of beds within facies ML2 which contain low-angle truncations, and their interpretation here as reworking features suggests that they have a different origin from the cross-bedded horizons within the American Tickle formation (facies AT4b).

3.3.4 Other Characteristics

At several horizons the Mainland formation shows evidence of sliding and partial incorporation of chaotic fine-grained material within the upper part of a sandstone bed (plate 3.14). These beds are similar to 'slurried sandstones' of Hiscott (1980) and are interpreted as being a result of intraformational sliding within the deposit.

At one horizon, large (>50 cm thick) bulbous features are present at the base of a medium (<30 cm thick) bed of sandstone (plate 3.15). These are interpreted as large load features.

Within the Mainland formation there are no obvious major thinning or fining upward sequences, although thick-bedded ML2 facies are overlain by finer grained facies. However as one goes upsection, particularly towards Low Point, the inferred top

Plate 3.14: Rubbly horizon in Mainland formation similar to 'slurried sandstone' of Hiscott (1978). Note large shale clasts. Three Rock Cove.

Plate 3.15: Large load features in the Mainland formation. Three Rock Cove.

of the section, the style of sedimentation changes from an essentially continuous sequence of sandstones/siltstones to thick packages of shale/siltstone interbedded with packages of sandstone. In addition, upper parts of the section appear to contain greater evidence of soft-sediment deformation, and cross-bedding is more prominent. At the inferred top ofthe Mainland formation, at Low Point (appendix 1, location map 1), there are several features which contrast with those lower in the section, notably the thickness of the cross-sets, the abundance of thick (30 cm) spectacular convolute laminations, and the apparently more mature, more calcareous, and more resistant nature of the sandstones.

Throughout the Mainland formation, horizontal feeding traces are common, and small (1 cm diameter) knob shaped protusions on the bases of some beds may be related to vertical burrowing in the finer grained material underneath. Botsford (1988) has suggested that ichnology is useful in determining the oxygen levels of bottom waters which may range from anaerobic (dissolved oxygen < 0.1 ml/l; no macrobenthos) to dysaerobic (0.1 - 1 ml/l; some macrobenthos) to aerobic (> 1 ml/l; abundant macrobenthos; abundant bioturbation). Savrda and Bottjer (1986) have suggested certain criteria based on the sizes of burrows and the depth of penetration of burrows to distinguish between relative oxygen levels within the general dysaerobic realm. This scheme was developed for pelagic sediments, so its applicability to sandstone units like the Mainland may be limited, but it is worthy of note that the Mainland formation is the only formation of the three Ordovician sandstone units which displays vertical burrowing, and horizontal traces which could be described as abundant. Vertical burrowing is considered to be an indicator of relatively higher levels of oxygen within the dysaerobic

realm, as tolerable oxygen levels penetrate to a greater depth within the sediment (Botsford, 1988). The higher overall oxygenation levels within the Mainland formation may indicate that the Mainland formation was deposited in shallower water than the American Tickle formation, or turbidity currents and possibly bottom currents periodically or constantly brought oxygenated waters into the basin. Botsford (1988) has suggested that an increase in bioturbation from the Cooks Brook Formation to the Middle Arm Point Formation in the Humber Arm Allochthon indicates an increase in bottom current activity.

At the main Three Rock Cove section (see appendix 2, location map 1) the paleocurrent directions are predominantly to the south, however at the section overlying the Cape Cormorant Formation south of the village of Mainland (see appendix 2, location map 1) paleocurrent directions are to the northwest.

In Victor's Brook, a locality not visited by the author, an occurrence of sandstone previously interpreted as a large clast in melange (Williams, 1984) has been reinterpreted by Corney (1991) as a continuous section through the upper part of the parautochthon which is terminated by the basal thrust of the Humber Arm Allochthon. Overlying the Table Head Group, Corney (1991) has recognised a sandstone unit similar to the Mainland formation which contains in its lower part a limestone conglomerate member similar to the Daniel's Harbour Member of the American Tickle formation. In the upper part of the section a number of conglomerate horizons occur which appear similar in their description to the Howe Harbour member, although large rafts of the Humber Arm Allochthon shales are incorporated in the section. The total thickness of the section

described by Corney (1991) is 500 m. Corney (1991) and Waldron (pers. comm. 1991) believe that this sandstone occurrence was once continuous with the Mainland formation although the two localities are now separated along the later Round Head shear zone. Corney (1991) does not record an upward coarsening within the sandstone part of the sequence, and in a similar fashion to the Hare Bay Allochthon, the arrival of the Humber Arm Allochthon is entirely recorded by the Daniel's Harbour and Howe Harbour lithologies and not by the sandstones.

3.3.5 Interpretation and Regional Considerations

The minimum thickness of the Mainland formation is 620 m, but before an overall interpretation of its sedimentological setting can be attempted, the question arises as to whether the formation might be as thick as the 1.5 km previously estimated (e.g. Stevens 1970; see Table 2.1). The contact of the Mainland formation with the underlying Cape Cormorant Formation appears conformable, but it has also been interpreted by several visitors to the outcrop (G. Jenner, pers. comm. 1992) as a bedding parallel fault which would presumably place younger material (Mainland) over older (Cape Cormorant). There are several other bedding parallel faults within the Mainland formation. If the limited faunal evidence available (Llandeilo age for fossils at Low Point, James and Stevens (1982)) can be believed, some of these faults may also place younger over older material, as younger Low Point lithologies would be thrust over older Mainland lithologies.

Stockmal and Waldron (1990) and Waldron and Stockmal (1991) have interpreted

the Mainland formation as being located in a triangle zone which has thrust the younger Long Point Group over the Mainland formation. Although the evidence observed by the author is admittedly limited, the sense of faulting within the Mainland formation in addition to the relationships outlined above would be consistent with an interpretation of them being smaller faults in the same sense as the main triangle zone fault.

In light of the above complexities, it is therefore difficult to obtain an accurate estimate for the thickness of the Mainland formation. If the interpretation of the structures in the above discussion is valid, younger material may have been thrust over older. If, on the other hand, the sense of thrusting is normal (i.e. older over younger rocks), sediments deposited closer to the basin axis (Low Point) may have been thrust over a succession which was more proximal to the eastern foreland basin slope.

Waldron and Stockmal (1991) have assigned the section of sandstones in Victor's Brook to undivided Goose Tickle group. They have interpreted the section through the Goose Tickle group in Victor's Brook in the following way. The approaching Humber Arm Allochthon caused flexure of the crust, which was accommodated by normal faulting along a reactivated rift related fault. The Cape Cormorant Formation (limestone conglomerates of the upper part of the Table Head Group which are restricted to this area) represents material eroded off the fault scarp. In the half graben generated during loading of the crust by the Humber Arm Allochthon, the Goose Tickle group was deposited, and includes material derived from submarine erosion of the toe of the Humber Allochthon (Waldron and Stockmal, 1991). As the Humber Arm Allochthon was emplaced, it incorporated slivers of Goose Tickle group into its chaotic base.

Sedimentation within the basin then ceased as the basin was overridden by the Humber Arm Allochthon, preserving a relatively undeformed section through the Goose Tickle group.

Other than describing the sandstones in the Victor's Brook area as similar to the Mainland formation, Waldron and Stockmal (1991) have not discussed the implications of the model for the main section at Mainland. The main Mainland and Three Rock Cove sections appear to have been located south of the southern termination of the Humber Arm Allochthon (although the western extent of the Humber Arm Allochthon is as yet unclear (Waldron and Stockmal, 1991)). As the minimum thickness of the Mainland formation at Three Rock Cove is 620 m, and no conglomerates or rafts of material derived from the Humber Arm Allochthon are present in the section, two possibilities exist. Either sedimentation in the main Mainland area went on after the emplacement of the Humber Arm Allochthon, or subsidence in this area was greater (which may be less likely at a greater distance from the allochthon), allowing for the deposition of a greater thickness of sediment. The model of Waldron and Stockmal (1991) clearly allows for continued deposition of Goose Tickle group equivalents in areas other than the Victor's Brook area subsequent to the arrival of the Humber Arm Allochthon. Therefore, the most likely explanation for the thick Mainland formation on the west coast of the Port au Port Peninsula, is that it represents sedimentation in the basin both during and after emplacement of the Humber Arm Allochthon. However, regardless of when sedimentation took place in the main Mainland area, there must have been a deeper depression to accommodate the sediment. Possibly this is related to a

greater degree of loading as a result of a thicker Taconic thrusted package in this area, or it may be related to the accommodation of subsidence along a reactivated rift fault, rather than by flexure.

It is clear that crucial to the hypothesis of the development of the Mainland formation in its upper parts is the relocation and recollection of the fossil locality at Low Point, as the interpretation of this outcrop as post Llanvirn would confirm that deposition of the Mainland formation continued subsequent to the arrival of at least the lower slices of the Humber Arm Allochthon (as inferred from the relationships between the American Tickle Formation and Howe Harbour member equivalents in the Victor's Brook area).

The Mainland formation is dominated by facies classes B and C of Pickering et al. (1986) and is interpreted as having been deposited by moderate and high concentration turbidity currents in the mid fan area of a submarine fan (e.g. Walker, 1984) under relatively well oxygenated conditions (cf. the American Tickle formation). As with the American Tickle formation the geometry of the fan cannot be documented and the system must be regarded as oversupplied. The fact that some localities at Mainland indicate paleocurrents to the northwest may indicate lobe switching, a feature reported by Hiscott (1980) in the Tourelle Formation and characteristic of areas of high topography. This would be consistent with structural models for the area which include a number of complex factors:

1) Large piles of sediment on the basin floor which now constitute the underlying Cape Cormorant Formation might have deflected turbidity flows in the Mainland formation;

2) The anomalous paleocurrent directions are most prevalent at the southernmost outcrop

of the Mainland formation, which is the closest to the St. Lawrence Promontory. Paleoflow in the Appalachian foreland basin tends to be away from major promontories (Hiscott et al., 1986);

3) Changes in the route of sediment supply might have been generated by the choking off of supply systems through the arrival of the lower sedimentary slices of the Humber Arm Allochthon in the Victor's Brook area.

The position of the Mainland mid-fan with abundant coarse sediment clearly implies the existence of another sediment input point in addition to those outlined in the discussion regarding the American Tickle formation. It should also be noted, however, that with mounting evidence of structural complexity in the parautochthonous sequence (Waldron and Stockmal, 1991) it is unclear whether the Mainland formation was closer to a sediment input point or whether it is simply a more marginal facies which has been transported westward relative to the more axial facies of the American Tickle formation. These two possibilities are not mutually exclusive. It is suggested that in view of the facies present, as well as the sand/mud ratio, that the former was the case.

The structure of the Mainland Formation is poorly understood but if relative vertical stratigraphic relationships are preserved, as is suggested by the limited available evidence, then the Mainland formation changes in character as one goes upsection. The apparent top of the exposed section (at Low Point) has thicker shale packages which are punctuated with sandstones which show spectacular convolute laminations, large scale scouring and cross-beds, and in places, overturned cross-bedding. Very strong bottom currents and/or dilute as well as concentrated turbidity currents are indicated by the

abundant cross-bedding. The increasing shale abundance might suggest an overall fining upward sequence such as was also suggested for the American Tickle formation.

If the beds at Low Point are indeed of Llandeilo/Caradoc age, liquefaction and overturned cross-bedding (e.g. Allen and Banks, 1972) indicates continued tectonic activity after the emplacement of the lower slices of the Humber Arm Allochthon, which would be consistent with current models for the area (Cawood 1989; Stockmal and Waldron, 1990; Waldron and Stockmal, 1991).

3.4 THE LOWER HEAD FORMATION

3.4.1 Introduction

The Lower Head Formation is exposed in a series of imbricate thrust slices in the area north of Bonne Bay, with smaller outcrops in Bay of Islands and in the Port au Port Peninsula area (appendix 1, location maps 3, 2, and 1). In this study most attention was paid to the area north of Bonne Bay, as the Lower Head Formation has been studied in the Bay of Islands area by Botsford (1988), and in the Port au Port Peninsula by Botsford (1988) and Gonzalez-Bonorino (1990). In all areas proportions of different sandstone facies present at each locality are variable and correlations between different outcrops are impossible. Paleocurrent information is also limited. However, information about the overall depositional context of the unit is available as the underlying Cow Head Group has been extensively studied (James and Stevens, 1986) as has the Northern Head group in the Bay of Islands area (Botsford, 1988). In addition, Gonzalez-Bonorino (1990) has conducted a detailed investigation of one locality of the Lower Head Formation in the

Plate 3.16: Facies LH1 (conglomerate and very coarse sandstone) of the Lower Head Formation. Note sandstone layer within conglomerate bed, and variation in clast populations between layers. St. Paul's Inlet.

Plate 3.17: Facies LH2 (medium- to very thick-bedded sandstone) of the Lower Head Formation. Note the concretions on fluid escape structures and shale chips. Lower Head North.

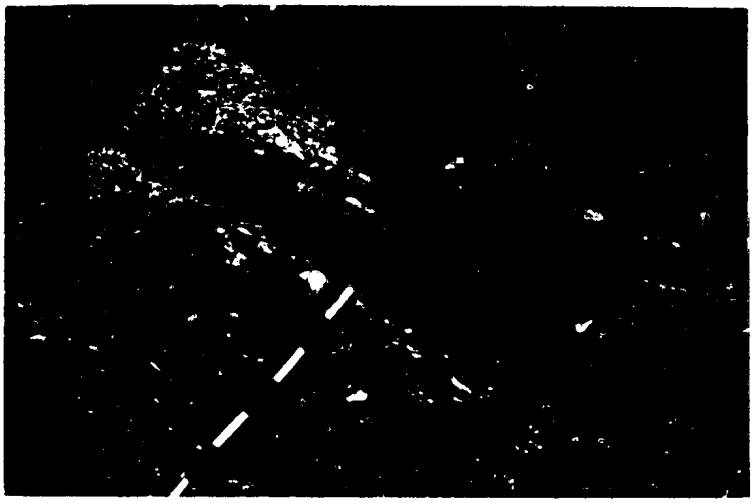


Plate 3.16: Facies LH1 (conglomerate and very coarse sandstone) of the Lower Head Formation. Note sandstone layer within conglomerate bed, and variation in clast populations between layers. St. Paul's Inlet.

Plate 3.17: Facies LH2 (medium- to very thick-bedded sandstone) of the Lower Head Formation. Note the concretions on fluid escape structures and shale chips. Lower Head North.

also be present. Paleocurrent data derived from measurements of preferred orientation of clasts parallel the regional paleocurrent direction as indicated by data from other facies.

Characteristics of the LH1 facies vary considerably from locality to locality. In the section at Martin Point South (appendix A2.3.1) lensoid conglomerate horizons occur at the bases of well-developed fining upward sequences. Similar features are also present at Black Point, where approximately 100 m of complex amalgamated coarse to granule sandstone is interbedded with minor conglomerate. At St. Paul's Inlet (appendix 1, location map 3), a 6 m thickness of LH1 occurs as an isolated outcrop, and conglomerate layers are complexly interbedded with sandstone layers. At Lower Head North, one conglomerate horizon which is less than 30 cm thick is traceable along strike for at least 1 km. At Portland Hill (appendix 1, location map 3) the prominent hill marks an occurrence of conglomerate within the Lower Head Formation which may be as thick as 450 m. Generally clasts are larger towards the top of the section and may reach boulder size. Exposure on the hill is limited, but the conglomerate layers are approximately 30 - 100 cm thick and may be inversely or normally graded. Despite the poor exposure, it is clear that the conglomerate is represented in numerous different horizons, rather than in a single bed.

Conglomerate of the Lower Head Formation contains a suite of pebble to cobble sized clasts which are exclusively sedimentary in origin, including a variety of limestones, red, green and black chert, pyrite nodules, and sandstones. The limestone and sandstone clasts are rounded, whereas the chert clasts are platy and subangular.

Relative proportions of clast types vary from layer to layer within conglomeratic horizons, imparting a marked inhomogeneity. It is therefore difficult to describe the conglomerates in terms of average clast composition, however, a list of clast types based on clast counts at two localities is given in table 3.2.

Comparisons with lithologies in the underlying Cow Head Group (James and Stevens, 1986), suggests that clasts in the Lower Head Formation are derived from lithologies similar to the Cow Head Group. The Cow Head Group can be described in terms of a set of numbered 'beds' which consist of limestone and limestone conglomerate with rounded clasts (even numbers) and shale and chert (odd numbers). James and Stevens (1986) noted that clasts in the conglomerate of the Lower Head Formation are identical to lithologies from the uppermost beds 10 through 15 of the Cow Head Group. Supporting this contention is the recovery of one limestone clast by the author which contained graptolites typical of the upper part of the Cow Head Group (S.H. Williams, pers. comm. 1991).

It is clear, despite internal inhomogeneities, that conglomerate units from different localities vary in overall clast content. For example, the conglomerate on Portland Hill is dominated by peloidal limestone and calcarenite clasts, whereas the conglomerate at St. Paul's Inlet contains a much higher proportion of red and green chert (see table 3.2). In addition, comparison of the lithologies of conglomerate clasts with directly adjacent lithologies of the Cow Head Group shows that the clast population within a specific conglomerate unit is largely similar to lithologies in the Cow Head Group immediately adjacent to the outcrop. The Cow Head Group in outcrops in the Portland Creek area

Table 3.2

Clast counts from Lower Head conglomerates

St. Paul's Inlet

1. Siliceous red mudstone (chert)	44
2. Siliceous green mudstone (chert)	29
3. Fine grained grey limestone	22
4. Coarse grained peloidal/bioclastic limestone	9
5. Laminated limestone	0
6. Impure dolomitic limestone	0
7. Fine - coarse grained sandstone	23
8. Coarse sparry limestone, cone in cone structure	0
9. Limestone/orange chert breccia and conglomerate	5
10. White sugary limestone	3
11. Pink crystalline limestone	0
12. Laminated red and green or grey and black chert	5

Portland Hill

1. Fine grained peloidal limestone (may be laminated)	107
2. Buff weathering grey silty or sandy limestone	1
3. Calcarenite, commonly laminated	28
4. Micritic limestone	1
5. Grey green argillite or chert	2
6. White - buff weathering grainy limestone	19
7. Green sandstone	5
8. Fossiliferous limestone	0
9. Light grey limy siltstone	2
10. Laminated dolostone	1

Clasts were defined as those greater than in 50 mm long diameter, and were counted on a grid spacing 10 cm apart at various angles to bedding.

is dominated by calcarenite and limestone conglomerate, whereas in the St. Paul's Inlet area, the Cow Head Group is characterised by red and green chert, and thinner limestone and limestone conglomerate horizons (some with chert and chert conglomerate caps). In the Rocky Harbour area, where conglomerate of facies LH1 was studied in some detail by Gonzalez-Bonorino (1990), distinctive black siliceous shale with pyrite nodules is characteristic of the Cow Head Group, and clasts of similar lithology are prominent in the Lower Head conglomerate. Conglomerate in the Bay of Islands area contains predominantly dolostone fragments which are typical lithologies in the underlying Middle Arm Point Formation in more easterly localities in the region.

No examples of facies LH1 were observed to occur at the base of Lower Head Formation, and the facies is not present in all sections. In sections where the conglomerate does occur, it is never found in the lowermost 'slump and injection' (Botsford, 1988) part of the formation.

Conglomerate of facies LH1 was included by Gonzalez-Bonorino (1990) in his facies association FA1 (thick-bedded sandstone and conglomerate). Here a separate facies class is introduced for thick- and very thick-bedded sandstone because in the Lower Head Formation as a whole there is abundant thick-bedded sandstone which is not very coarse-grained and is not associated with conglomerate. However the finer grained examples of facies LH1 may be gradational with facies LH2. The Lower Head conglomerate is not easy to classify using the scheme of Pickering et al. (1986), which seems to lack sufficient detail for the classification of conglomerates. Facies LH1 appears to belong to facies A but does not conform precisely to any of the subclass descriptions, and upper

parts of conglomerate horizons resemble facies class B2.1.

A more useful discussion of conglomerate classification is given by Surlyk (1984). According to the descriptions given by Surlyk (1984), conglomerates of the Lower Head Formation seem to correspond mainly to his facies 9 (graded, matrix-supported conglomerate with random fabric), 10 (graded, matrix-supported, imbricated conglomerate), and 14 (conglomerate grading into sandstone). Facies 6 (inverse to normally graded, matrix-supported conglomerate) is also present in some places. At St. Paul's Inlet, the conglomerate beds might best be described in terms of Surlyk's (1984) facies 13 (composite conglomerates) in which sandstone layers are complexly interbedded with conglomerate layers.

Facies 9 and 10 are interpreted by Surlyk (1984) to have been deposited as a result of direct suspension from high-density turbidity currents, facies 6 was deposited by frictional freezing of a basal traction carpet followed by suspension sedimentation from high-density turbidity currents, and facies 14 represents a fining upward sequence deposited by surging flows. It should be noted that according to Surlyk (1984), most of the descriptive features of a conglomerate, such as inverse grading and imbrication, provide information on the hydrodynamic conditions of deposition and may provide little information on the proximity of the flow to the head of a fan or to the source.

The composite conglomerate, facies 13 (first described by Hendry, 1973) was likely deposited by successive pulses of coarse grained gravity flows resulting from progressive headward failure on a slope. Comparison of the Lower Head conglomerates, particularly those at St. Paul's Inlet, with those described by Hendry (1973) shows many

similarities, including large size and poor sorting of the clasts, 'floating' nature of many of the clasts, common preferred orientation of a axes of the clasts, erosional bases, and the existence of layers of sandstones within the conglomerates. Although sandstone layers are not present in all conglomerate beds of the Lower Head Formation, they are present in several (see plate 3.16) and their presence, in addition to the variation in clast types between the conglomerate layers, suggests that several different events may have contributed to the deposition of one bed, thus allowing for application of the term 'compound' (Hendry, 1973).

Rip-up clasts within the Lower Head conglomerate horizon were not observed, again similar to the situation described by Hendry (1973). Hendry (1973) interpreted this to mean that the transport energy of layers arriving at the depositional site did not vary sufficiently to allow erosion and deposition to alternate during the buildup of the compound beds, and suggested that individual layers within the beds were related to each other in time and space, thus qualifying these beds for the term 'composite'. Hendry (1973) suggested that sands which now constitute the sandy matrix to the conglomerates were previously deposited further upslope and were subsequently liquefied, possibly by an earthquake. An upper layer of sand would be transported as a gravity flow down slope, leaving a newly exposed layer subject to backrush, liquefaction and failure. Thus several successive failures would occur to complete the buildup of the composite bed.

The presence of fining upward sequences, abundant amalgamation surfaces, and a deep basal scour at Martin Point North suggest that here the conglomerates were deposited in a channel. The same may also be true of the locality at Black Point where

similar features are observed, although the abundant scouring and less well developed fining upwards sequence may indicate a shallower channel. Similar features in submarine facies have been described by Hein and Walker (1982). Thus a number of different processes may have contributed to the deposition of facies LH1.

The fact that within any one conglomerate bed, different layers may be dominated by different clast types (plate 3.16) is interpreted as the signature in successive clast populations of derivation from different beds of the Cow Head Group. The very local relationship between the conglomerate clasts and the underlying units is somewhat at odds with the fact that the clasts are rounded and were lithified before becoming incorporated in the Lower Head conglomerates. It has been suggested that red and green cherts of the Cow Head Group have undergone early lithification (James and Stevens, 1986). Limestone clasts of the Lower Head conglomerates are single limestone fragments only and no limestone conglomerate clasts have been found, suggesting that although the chert in the Cow Head Group was lithified, the limestone conglomerate had not yet been cemented by the time of the incorporation of these lithologies into the Lower Head Formation. Rounded sandstone clasts are interpreted as eroded concretions which had an original spherical shape, and these are also typically lithified early (Hiscott, 1978). Thus it is suggested that the Cow Head Group (and Lower Head Formation) was eroded in a post-early lithification phase.

Comparison of the clast population of cobbles in the Lower Head Formation conglomerate with the sandstone and granule matrix shows that the matrix contains grains of lithologies similar to the conglomerate clasts, but in addition contains grains typical

of the entire range of rock fragments and other framework grains found in the Lower Head Formation (see chapter 4). In fact, perhaps because the granule sandstones associated with these conglomerates are coarser than the average Lower Head Formation lithologies, matrix to the conglomerates contains the widest variety of volcanic rock fragments seen in the unit. Volcanic rock fragments are never found as cobble-sized clasts in the conglomerate. Clearly this implies a mixing of a clast population derived exclusively from local examples of the Cow Head Group, with the overall grain population supplied to the Lower Head Formation proper. Neither Surlyk (1984) nor Hendry (1973) discussed the relationship between conglomerate clasts and matrix in detail. Hendry (1973) did imply a difference in composition between grain types of clasts and matrix, although he did not explore the implications of this.

Thus any hypothesis explaining the origins of facies LH1 conglomerate must take into account the following observations:

1. The conglomerate in general was deposited by high density turbidity flows;

2. Some conglomerate was deposited in channels (of varying depth) and some appears to represent composite beds sensu Hendry (1973) which were deposited by successive failure on a submarine slope;

3. The conglomerate horizons never occur at the base of the Lower Head Formation;

4. The clast populations of the matrix and the conglomerate are not the same;

5. The clasts in the conglomerate consist exclusively of Cow Head Group and Lower Head lithologies and appear to be very locally derived;

6. Chert clasts are platy, limestone and sandstone clasts are rounded, and no clasts of

limestone conglomerate have been found.

3.4.3 Facies LH2: Thick- to Very Thick-bedded Sandstone

Facies LH2 is dominated by thick- to very thick-bedded, massive, medium- to coarse-grained sandstone (plate 3.17). Particularly in the Bay of Islands area, beds may be as great as 10 m thick, although it is unclear as to whether some of these beds may be amalgamated. Bases of the beds are commonly non-erosive and tops tend to be friable and poorly defined, suggesting a poorly developed normal distribution grading. The only structures commonly displayed by the sandstone are a variety of fluid escape structures and concretions. The fluid escape structures are cemented by calcite and are resistant to weathering. Concretions occur as spherical features in which calcite cementation has nucleated around shale chips (cannonball concretions), and in continuous rinds or layers up to 10 cm thick which may reflect bedding parallel variations in the mud/sand ratio within the bed, which are otherwise invisible to the naked eye. Some beds display a crude parallel stratification defined by coarser and finer layers of sand which may show inverse - normal grading within the layers. The bases of the beds may contain large flutes (20 cm wide) or grooves, and horizontal feeding trace fossils are present on the bases of a few beds. Botsford (1988) has identified a suite of trace fossils in the Lower Head Formation dominated by Cosmorhaphe and Paleodictyon, which he considered to be typical of the low diversity Nereites ichnofacies, and which moreover are characteristic of a 'flysch related assemblage'. Facies LH2 sandstone beds are laterally continuous within the scale of the available outcrop, but may be amalgamated; however,

the amalgamation surfaces are difficult to see given the generally structureless nature of the sandstones. Minor tangential cross-bedding in sets approximately 20 cm thick may occur on the tops of the beds.

Facies LH2 sandstones are interpreted as belonging to facies classes B1.1 (Thick/medium-bedded disorganised sands) of Pickering et al. (1986), and beds displaying crude parallel stratification, belong to the related class B2.1 (Parallel-stratified sands). Both types were deposited by high concentration turbidity currents with the massive type being deposited by freezing or subsequent liquefaction of a flow, whereas the stratified type is interpreted as having been deposited by freezing of traction carpets at the base of the flow (Pickering et al., 1986). The cross-bedded tops of beds are interpreted as being the result of reworking by dilute turbidity currents. Thus the suggestion that facies LH1 and LH2 may be gradational is reasonable.

Facies LH2 was included by Gonzalez-Bonorino (1990) in his facies association 1, thick-bedded sandstone and conglomerate.

3.4.4 Facies LH3: Medium- to Thick-bedded Rippled Sandstone

Facies LH3 consists of medium- to thick-bedded sandstone showing multiple sets of climbing ripples as the dominant sedimentary structure (plate 3.18). This type of sandstone is notably calcareous in comparison to most sandstones of facies LH1 and LH2.

Facies LH3 sandstone may be classified as C2.2 (medium-bedded sand-mud

Plate 3.18: Facies LH3 (thick-bedded calcareous sandstone with climbing ripples) of the Lower Head Formation. Lower Head South.

Plate 3.19: Thin- to medium-bedded sandstone (LH4), dolostone (LH7 - light weathering bed on left), and mudstone (LH6), of the Lower Head Formation. Western Brook Pond North.

couplets) although grading is not well developed. This facies was probably deposited from high concentration turbidity currents (Pickering et al., 1986). Gonzalez-Bonorino (1990) has suggested that the thickness of facies LH3 beds implies that they were fed by long-lived turbidity currents such as those supplied by rivers in flood. However, their association with slump folding and other indicators of soft sediment deformation might indicate a derivation directly from repeated slumping.

3.4.5 Facies LH4: Thin- to Medium-bedded Sandstone

Facies LH4 consists of thin- to medium-bedded, medium-grained sandstone showing well developed Bouma sequences with T_{ace} as the most commonly preserved sequence. On some rippled surfaces, particularly in examples of LH4 in the Bay of Islands, rill markings are developed on the rippled surfaces, and these have been interpreted as being small scale load features (e.g. Allen, 1984).

Facies LH4, with its classical turbidite aspect belongs to facies class C2.3 (thin-bedded sand mud couplets) which were deposited by low concentration turbidity currents (Pickering et al., 1986).

3.4.6 Facies LH5: Thin-bedded Rippled Calcareous Sandstone

Facies LH5 consists of thin-bedded fine-grained calcareous sandstone. This facies is similar to facies LH4 except for its predominantly calcareous nature and its finer grain size. The beds are thin and weather white or tan. T_{ace} Bouma sequences are well preserved.

The interpretation of these beds is similar to that for facies LH4, as the classical turbidite features of these beds place them in facies class C2.3 (thin-bedded sand mud couplets) of Pickering et al. (1986), which were deposited by low concentration turbidity currents.

3.4.7 Facies LH6: Mudstone

Mudstone in the Lower Head Formation tends to weather recessively, is green in colour and is massive. On most of the coastal sections studied it is poorly exposed. Facies LH6 is present in abundance only at the shoreline section south of Portland Creek (see appendix 1, location map 3). Other examples of facies LH6 occur at Western Brook Pond where the mudstone ranges from black to grey in colour and is interbedded with thin to medium beds of dolomitic siltstone.

Both mudstone and the associated dolomitic siltstone were included by Gonzalez-Bonorino (1990) in his facies association 4. Facies LH6 most resembles facies E1.1 (structureless muds) of Pickering et al. (1986) which may have been deposited by hemipelagic settling or by the ponding of thick turbidity currents. There is no evidence for the existence of megaturbidites in the Lower Head Formation. Megaturbidites are associated with shallow slopes and therefore would not be expected to be associated with olistostromes. Thus the association of mudstone in the Portland Creek area with thick sandstone beds and an olistostrome, and in Western Brook Pond with dolomitic siltstone, suggests that in both cases the mudstone was deposited by hemipelagic settling.

3.4.8 Facies LH7: Dolomitic Siltstone

Facies LH7 consists of thin- to medium-bedded buff- to tan- weathering dolomitic siltstone which is massive to ripple cross-laminated (plate 3.19). This facies is only exposed in the Rocky Harbour area (Gonzalez-Bonorino, 1990) and in Western Brook Pond. It is associated with Facies LH6 mudstone.

Facies LH7 probably belongs to facies class D2.1 (graded-stratified silts) and was deposited by low concentration turbidity currents (Pickering et al. 1986). Gonzalez-Bonorino (1990) included both facies 5 mudstone and facies 6 dolomitic siltstone in his facies association 4. He did not, however visit the Portland Creek locality to observe that mudstone need not necessarily be associated with dolomitic siltstone.

3.4.9 Facies LH8: Chaotic Pebbly Mudstone

Two subfacies of chaotic pebbly mudstone are present in the Lower Head Formation:

Subfacies a) consists of pebbles and cobbles of sandstone and limestone sparsely distributed in a chaotic matrix of green and red shale. This facies is present in the lower 30 m of the Lower Head Formation only and is present at the Martin Point North section (appendix 1, location map 3; appendix 2, section A2.3.1). The maximum thickness of this horizon is about 5 m.

Subfacies b) is exposed only in the shoreline section south of Portland Creek (appendix 1, location map 3) and is composed of large cobbles and boulders of sandstone distributed in a muddy/and or sandy matrix. Some of the clasts within the deposit are

themselves brecciated, and angular (plate 3.20). The thickness of this horizon is about 15 m.

Both subfacies are interpreted as olistostromes, and the extent of internaldeformation within both subfacies probably places each of them within facies class F2.2 (dislocated, brecciated and balled strata). Subfacies a) is predominantly a deformation of unlithified Cow Head lithologies, whereas subfacies b) is completely intraformational to the Lower Head Formation.

Neither of the above subfacies were recognised by Gonzalez-Bonorino (1990).

3.4.10 Other Characteristics and Local Interpretations

An almost ubiquitous characteristic of the lower part of the Lower Head Formation is a zone of deformation of shale associated with injection of sandstone dykes and sills (plate 3.21). This zone, which was referred to by Botsford (1988) as the 'slump and injection facies', is of variable thickness, but can extend up to 60 m above the base of the formation. Sandstone dykes and sills are present in the sections at Western Brook Pond, and slumping associated with the formation of olistostromes is present at Martin Point North. Both slumping and injection features are present near the base of the Lower Head Formation in the Bay of Islands area (Botsford, 1988), and sandstone dykes are present at the base of the formation in the Rocky Harbour area. Hiscott (1979) has noted similar features at the base of the Tourelle Formation in Quebec, and has related their presence to the existence of impermeable shale in the section which acted as a seal and promoted liquefaction and intrusion of sands.

Plate 3.20: Facies LH8 (pebbly to cobbly mudstone) of the Lower Head Formation. This is subfacies b. Portland Creek.

Plate 3.21: Sandstone dykes in sandstone of the Lower Head Formation. Western Brook Pond South.

At one locality in the Bay of Islands, Botsford (1988) noted that the red and green shale of the Midd'e Arm Point Formation which underlies the Lower Head Formation in this area were deformed prior to deposition of the Lower Head Formation. At Martin Point South, complex slump folding is present in sandstone near the base of the section. Also present is a gradual steepening of the dip of the beds, which become suddenly shallower dipping at the base of the major conglomerate horizon within the section. No clear evidence of tectonism is associated with this feature, and it may in fact be a preserved angular unconformity within the section.

Gonzalez-Bonorino (1990) did note the presence of slumping within the Lower Head Formation, but suggested that interlobe relief may be sufficient to account for it. This author disagrees, for three reasons:

1. Slumping occurs at the bases of several of the measured sections, and in at least one case prior (Botsford, 1988) to the deposition of the Lower Head Formation. This implies uplift of a slope prior to and during the early phases of deposition of the formation;

2. Slumping occurs within red and green shale, lithologies which are not part of the lobes of the Lower Head Formation fans, also indicating a pre-existing slope or contemporaneously deforming slope;

3. The clasts in the Portland Hill conglomerate are predominantly peloidal limestone and calcarenite, which are more characteristic of lower parts of the Cow Head Group (James and Stevens, 1986). Nowlan and Barnes (1987) reported the occurrence of clasts containing Lower Ordovician conodonts, and the apparent lack of clasts representative of the upper part of the Cow Head Group may indicate a prior phase of erosion of the

Cow Head Group. (Note that Nowlan and Barnes (1987) interpreted the Portland Hill Conglomerate as part of the Cape Cormorant Formation). This observation, and the suggestion by James and Stevens (1986) of erosion of the Cow Head Group prior to deposition of the Lower Head Formation in places, implies uplift (and presumable formation of a slope) of that unit prior to the deposition of the Lower Head Formation.

James and Stevens (1986) have suggested that the Lower Head Formation was deposited in a submarine fan setting. The outcrops of the Lower Head Formation at Rocky Harbour have been interpreted by Gonzalez-Bonorino (1990) as having been deposited in shallow, braided, frequently migrating channels in the proximal areas of submarine fans. The channels he interpreted as his facies association 1 (thick-bedded sandstone and conglomerate), and at the mouths of these channels he recognised lobes (his facies association 2, medium to thick-bedded sandstone). Other facies associations he interpreted as having been deposited on the fringes of lobes or in interlobe areas. He interpreted climbing rippled sandstones (assigned in this study to facies LH5) as the result of deposition from continuously fed turbidity currents which were generated by discharge from small rivers during their flood stages. He suggested that a number of fans probably existed in the area, each with their own separate feeder channel. The author is in general agreement with Gonzalez-Bonorino (1990) and James and Stevens (1986) that the general domination of facies classes A and B in the Lower Head Formation, with lesser amounts of C, D, and E suggest deposition primarily in an upper or mid 'fan' setting. Nevertheless, a few cautionary points should be made.

1) Gonzalez-Bonorino's (1990) main area of study was the Rocky Harbour area, which,

although it is a good wave cut platform section of the rocks and allows for determination of lateral variations, is structurally complex and is part of a dismembered raft in melange. The building of a regional basin model based largely on this one outcrop may be suspect.

2) The suggestion by Gonzalez-Bonorino (1990) that the presence of conglomerate indicates proximality is in conflict with the statements of Surlyk (1984). Surlyk (1984) has argued that in the well exposed Wollaston Forland Group, Greenland the following facts can be determined: there is no down slope change in conglomerate facies to aid one in determining a proximal/distal relationship; conglomerate flows appear to have originated from all parts of the slope, hence were not necessarily derived from the fan apex, again rendering the suggestion of proximality suspect.

3) The Lower Head Formation as a whole satisfies the criteria outlined by Hiscott et al. (1986) and must be considered 'grossly oversupplied'.

To provide a more regionally based model it is appropriate to summarise and interpret the characteristics of some of the main Lower Head localities. The sections at Martin Point North and South are dominated by facies LH2 thick-bedded sandstones with slumped horizons at their bases. Martin Point South and Black Point contain examples of LH1 which is overlain in a succession of fining upwards sequences 10's of m thick by monotonous sandstone of facies LH2. Multiple shallow scouring is particularly well developed at Black Point.

Lower Head South, and Western Brook Pond North and South, contain substantial monotonous packages of facies LH2 thick-bedded sandstone, but also include a greater

proportion of other facies, notably representatives of facies LH3, LH4, LH5, and LH6. The Western Brook Pond localities show interbedding of Cow Head lithologies for a considerable thickness above the base of the Lower Head Formation (see appendix 2; section A2.3.3). These features suggest that sediments from these localities were deposited closer to interlobe areas or on the fringes of the lobes. The presence of calcareous sediments of LH5 and LH7 may indicate periodic reversions to supply of material from carbonate rocks on the western side of the basin.

Southwest of the Portland Hill conglomerate, approximately along strike, the Lower Head Formation is characterised by 20 - 30 m packages of facies LH2 sandstone interbedded with 20 m thick packages of LH6 mudstone. The sandstones in the upper part of this coastal section display layers and thin beds of granule conglomerate containing a similar suite of clasts to those found on Portland Hill. Towards the top of this section an intraformational olistostrome (facies LH8, subfacies b) is also found. The area of the shoreline section where the granule layers are found may be approximately downcurrent from the main conglomerate on Portland Creek Hill (although the map of Cawood and Williams (1986) postulates a thrust between the two localities). If these two outcrops are continuous, the relationship might imply a rapid downcurrent thinning of conglomerate beds, and a downcurrent reduction in grain size of clasts. A more likely theory hinges on the interpretations of the associated mudstone and olistostrome as slope facies. In this case the Portland Hill conglomerates could represent a major channel incised into a slope, with the shoreline packages of sandstones and granule conglomerates possibly representing channel overspill.

3.4.11 Interpretation and Regional Considerations

The outcrops of the Lower Head Formation at Rocky Harbour have been interpreted by Gonzalez-Bonorino (1990) as representing deposits in shallow, braided, frequently migrating channels. This interpretation was based on the fact that conglomerates are present as a channel fill (the geometry of the channel-fill can be documented in the case of the Rocky Harbour outcrop), but that the fill was apparently non-erosive. Gonzalez-Bonorino (1990) drew analogies between deposits of the Lower Head Formation at Rocky Harbour, and the Cape Enrage Formation in Quebec, which was studied by Hein and Walker (1982).

It is clear that conglomeratic facies at most localities are separated from underlying facies by an erosive contact. Demonstration of channel dimensions equivalent to those described by Hein and Walker (1982), particularly width, is difficult given the type of outcrop, but the at least 15 m of downcutting implied for the Martin Point South locality is on a comparable scale to that described by Hein and Walker (1982). A deep but narrow channel is suggested as an interpretation for the Portland Hill conglomerate. At Martin Point South and Black Point the overall fining upwards sequences appear to be of a similar scale to those interpreted by Hein and Walker (1982) as being indicative of the migration of a channel terrace over a channel fill. A shallower channel may be implied by the multiple scouring and relatively minor conglomerate facies at Black Point. Surlyk (1984) has suggested that all conglomerates need not have been deposited in channels derived from the apex of a fan, but could have been originated through slope

failure at any point on the fan, an explanation which may account for the composite beds observed at St. Paul's Inlet. In other parts of the Lower Head Formation (e.g. Western Brook Pond), with a greater variety of facies, the existence of channels cannot be established and the associations present are more similar to the unchanneled associations described by Hein and Walker (1982). Thus the Lower Head Formation overall is far more variable and contains a greater number of facies than those outlined by Gonzalez-Bonorino (1990).

Caution should be exercised in too slavishly applying the model of Hein and Walker (1982) for two reasons. Firstly, the conglomerates of Hein and Walker (1982) were deposited in a passive margin setting at a considerable distance from the source, and secondly all of the deep and shallow channels recognised by Hein and Walker (1982) were interpreted as having been formed as part of a braided system within a 300 m deep, 10 km wide deep sea channel deposit. With regard to the first point, it should be expected that local tectonic effects will have a greater effect on the sedimentology than in the case described by Hein and Walker (1982). With respect to the second point, the analogy may yet be valid, if it can be demonstrated that the Lower Head Formation was deposited in a system with a similar geometry to that described by Hein and Walker (1982).

The rounding of some of the clasts in the Lower Head conglomerate suggests that they may have resided briefly in a fluvial, beach, or shelf setting, although it should be noted that the limestone clasts in particular may have been rounded in a previous sedimentary cycle. The local derivation of the clasts is consistent with the concept that

the shelfal area was narrow in close proximity. The simplest way to account for local derivation of clasts in the Lower Head Formation is for gravity flows to have directly eroded the underlying Cow Head Group. Thus clasts in the conglomerate would simply be construed as rip-up clasts, although they are not intraformational. This hypothesis might be supported by the fact that the bases of most conglomerate horizons are clearly erosive. Hendry (1973) stated that the bases of composite conglomerates are erosive and the flows that deposited them were capable of eroding 'sandy and muddy substrates'. He did not clarify whether the flows might have been strong enough to erode lithified sediment.

Evidence of erosion of the Cow Head Group is provided by the work of Botsford (1988) which has indicated that at St. Paul's Inlet, bed 14 of the Cow Head Group is missing, and Lower Head sandstone directly overlies bed 13. In addition, at Portland Hill, the uppermost beds of the Cow Head Group do not appear to have been available to supply clasts to the Lower Head conglomerate at Portland Creek Hill. However, this phase of erosion appears to have occurred before deposition of the lower part of the Lower Head Formation which is generally characterised by non-erosive thick-bedded sandstone of facies LH2. Thus, if the hypothesis that gravity flows eroded the Cow Head Group is correct, the flows must have travelled over an area of semi-lithified Cow Head Group which was exposed subsequent to the initial phases of deposition of the Lower Head Formation. If the clasts are rip-up clasts, rip-up must have taken place a considerable distance from the area of deposition of the conglomerates while the flows were in an erosive phase. The range of grain sizes of the clasts from sand to cobble, the

variety of clasts implying substantial erosion through several beds of the Cow Head Group, and the size of the largest clasts relative to the thickness of individual depositional events are all atypical of rip-up clasts and of erosion in a deep-marine setting (R. Hiscott, pers. comm., 1991). In addition, the degree of lithification of the clasts which is implied by their internal integrity and the platy shapes of the chert clasts may argue against this hypothesis.

A second and favoured alternative involves subaerial exposure of the Cow Head Group. Rivers which supplied the main body of Lower Head sands may have eroded the Cow Head Group. In addition, the Cow Head Group, which was partly lithified, was progressively uplifted and formed scarps which may have generated local fan deltas at the margins of the basin which were independent of the main clastic supply. The fan deltas would have, at their toes, overlain and intertongued with sands from the Lower Head Formation which may have onlapped the slope, and which were supplied by more widely mixed sources from further afield.

The fact that different conglomerate layers are dominated by different populations of clasts, indicates successive erosion of different beds of the Cow Head Group and suggests that one might expect to observe an unroofing relationship within the conglomerates. In this case, sandstone clasts might be expected to be most common at the bases of the conglomerates as the Lower Head Formation overlies the Cow Head Group. Gonzalez-Bonorino (1979) observed that sandstone clasts become more prominent towards the top of the Rocky Harbour conglomerate unit, implying that sandstones may have been unroofed later, and were therefore underneath rather than on

top of Cow Head Group sediments. This may support the local fan delta hypothesis outlined above. Similarly, the increase in size of conglomerate clasts upsection at Portland Hill may also support a reverse unroofing hypothesis.

Conglomerates are never found directly at the base of the Lower Head Formation, implying that there was a phase marked only by siliciclastic deposition prior to the major uplift of the faults which generated the detritus supplied by the Cow Head Group.

Taking all aspects of the above discussion into account, the history of deposition of the Lower Head Formation might be as follows:

1. Uplift of the Cow Head Group from the east, probably along faults, accompanied by or followed by erosion which, in places, imparted substantial topography to the basin floor;

2. Sudden influx of Lower Head sands to the base of the slope, with continued uplift implied by slumping, and rapid deposition implied by injection features;

3. A second phase of uplift (or a drop in sea level, see Fortey, 1984), accompanied by erosion and rejuvenation of the main source of sediment which supplied coarse sand and granule material to the Lower Head Formation. The main supply systems or lesser tributaries may have eroded and incorporated material derived from local uplifts of the semi-lithified Cow Head Group. Lower Head sands may also have onlapped the upper slope and may have been intercalated with Cow Head Group lithologies which were deposited by small local fan deltas on the margin of the basin. Slumping on the high slope may have resulted in multiple related flows (composite beds), multiple unrelated flows (simple beds) and supply through main feeder channels may have resulted in

deposition in deep channels, shallow channels, and lobe and interlobe (unchannelised) areas.

Evidence used to support the existence of fan delta supply systems is as follows (Nemec and Steel, 1988; Surlyk, 1984):

1. The apparently proximity of the shelf to the basin as indicated by the local relationships of the Cow Head clasts in LH1 conglomerates;

2. The abundance and diversity of conglomerate and sand facies is similar to those described by Surlyk (1984) as having been deposited in submarine fans fed by a fan-delta system;

3. Lack of evidence for fan progradation which could have resulted in a large scale coarsening upwards cycle. Surlyk (1984) interpreted this to reflect the fact that in submarine fans fed by fan deltas, the steepest slopes and deepest water occur immediately adjacent to the source area;

4. Proximity to an orogenic system in which faulting is likely to have taken place, generating steep slopes.

Nemec and Steel (1988) suggest that the only unequivocal evidence for a fan delta is the demonstrated existence of an alluvial fan supplying the system. There is clearly no evidence for this in the Lower Head Formation. This, however, is not unexpected since both Surlyk (1984) and Massari and Colella (1988) suggest that the subaerial part of a fan-delta may have a poor preservation potential.

Belt and Bussieres (1981) have described foreland basin deposits of the Beaupre Formation, Quebec as having been deposited on a submarine fan fed by a fan-delta.

They postulated a fan-delta because 'it is as probable as a classical delta'. It is here suggested that the hypothesis of a fan delta supply to the Lower Head Formation is more strongly supported by the evidence than that postulated for the Beaupre Formation by Belt and Bussieres (1981).

Gonzalez-Bonorino (1990) has suggested that the Lower Head Formation and the Goose Tickle Group were deposited in the same foreland basin. Hiscott et al. (1986) considered that the Arenig Tourelle Formation in Quebec, which is similar to the Lower Head Formation in many respects, was deposited in trench slope basins. The evidence cited was that the Tourelle was deposited on uplifted and probably tilted slope and rise sediments. Also the transition from passive margin slope and rise deposits into coarse grained thick bedded sandstones of facies groups B and C (Hiscott et al., 1986) in the Tourelle Formation is abrupt with slides, slide scars and sandstone injections.

As described above, similar, although not identical features are observed in the Lower Head Formation. The lower slump and injection part of the sequence (which is also present in the Tourelle Formation, (Hiscott, 1979)) indicates that deformation and uplift was early with respect to the time of deposition of the Lower Head Formation. In the Lower Head Formation, no obvious slides have been observed, however the transition from the Cow Head Group is abrupt, erosion has occurred, and there is a zone of injection. These features were believed by Hiscott et al. (1986) to be more consistent with rapid introduction of sands into a small slope basin, or onlap of sheet or channelled sands onto a pre-existing slope, than with gradual progradation of a turbidite system into a larger foreland basin. The general conditions of deposition of the lower part of the

Lower Head Formation are characterised by uplift and slope formation, and contrast strongly with those in the Goose Tickle group which are characterised by subsidence.

Trench slope basins, described by Moore et al. (1980) in the Sunda trench system are continuous along strike for only a short distance (a few tens of kilometres) and the basin floors generally exhibit an irregular topography. The highest basins fill first, then sediment spills over into the lower slope basins. But as small basins begin to fill they generally coalesce to become larger basins. Therefore the largest basins are towards the top of the slope, and smaller discontinuous ones are towards the bottom. The position of the Lower Head Formation in this model would depend on whether the Bonne Bay, Bay of Islands, and Port au Port localities are part of the same basin.

Nemec and Steel (1988) have shown that a fan-delta supplying a confined system will have an extensive and well developed braid plain system. Given this information, it is suggested that the analogies drawn here between the facies observed in the Lower Head Formation and those observed by Hein and Walker (1982) in the Cape Enrage Formation may in fact be apt. In the case of the Lower Head Formation, the confining geometry would not be provided by a deep sea channel as in the case of the Cape Enrage Formation, but by the long, narrow shape of the trench-slope basin itself.

3.5 SUMMARY AND CONCLUSIONS

Broad regional facies analysis indicates that the American Tickle formation was deposited under anoxic conditions on a trench floor, probably as the outer lobes of

elongate submarine fans whose geometry was determined by the narrow elongate shape of the foreland basin. At least two sediment supply points allowed input of detritus to the American Tickle formation, and sediment supply was from the east. No evidence was found for the existence of structural highs within the basin.

In tectonic reconstructions of western Newfoundland the provenance of the Goose Tickle group has been deemed important in that detritus in these rocks has been thought to place constraints on the time of arrival of the Humber Arm and Hare Bay allochthons (Stevens, 1970; Stockmal and Waldron, 1990). Conventional wisdom has it that sandstones of the Goose Tickle group were shed directly off the Humber Arm and Hare Bay allochthons (Stevens, 1970; Cawood et al., 1988; Bradley, 1989). The only sedimentological indication in the Goose Tickle group of the imminent arrival of the allochthons is given by the coarsening upward turbidites and debris flows of the Howe Harbour member which were precursors to the olistostromes of the Northwest Arm Formation. This would imply a Middle Llanvirn age for the emplacement of this slice of the Hare Bay Allochthon. However, there appears to be no relationship between the distribution of sandstone lithologies of the Goose Tickle group and the arrival of either the Hare Bay or Humber Arm allochthons.

The Mainland formation was deposited during the Llanvirn and possibly Llandeilo in the mid fan area of an oversupplied submarine fan or fans in an area of higher topography and greater sediment supply, and more oxygen-rich waters, than the American Tickle formation, with lobe switching or overlapping lobes being indicated. The Mainland formation was probably deposited close to a third sediment input point

within the main foreland basin, and closer to the eastern margin of the basin. However, caution should be applied in making regional reconstructions along the length of the basin using sand/mud ratios alone, in the light of structural complexities involving the parautochthon (Stockmal and Waldron, 1990; Waldron and Stockmal, 1991)

The Lower Head Formation was deposited during the Arenig to early Llanvirn in an oversupplied basin or basins in which facies associations characteristic of middle and inner submarine fans were deposited. Deposition was accompanied by uplift, probably along faults on the eastern margin of the basin. It was also accompanied by probable subaerial erosion of stratigraphically older units and supply of the eroded material to the basin in addition to sediment derived from the main source of sand. Contrary to the suggestion of Gonzalez-Bonorino (1990), the Lower Head Formation was probably deposited in a slope basin or basins separate from the main foreland basin floor. The lack of lateral continuity of the formation within the allochthon may support the hypothesis that it was deposited in several short discontinuous basins, rather than in one long basin.

Although field sedimentology suggests that the Lower Head Formation was deposited in a slope basin, as opposed to the foreland basin proper, provenance studies may provide independent evidence for this. If, as Gonzalez-Bonorino (1990) suggests, small fans in the Lower Head Formation were fed directly by small rivers, this mode of supply might have resulted in a significant variation in grain population supplied to each individual system, which would suggest that the Lower Head Formation might be predicted to be petrographically heterogeneous. Clast populations in the conglomeratic

facies are certainly variable, but it will be investigated in Chapter 4 whether the sand-sized sediment displays the same heterogeneity.

CHAPTER 4

PETROGRAPHY

4.1 INTRODUCTION

Considerable attention has been paid in recent years to the study of provenance of turbidites. Two approaches have been taken to the collection and interpretation of petrographic data from sandstones. The first was outlined by Zuffa (1985, 1987, 1991) who relied on a qualitative, interpretive approach, and recognised the loss of information which occurs when most quantitative methods are applied. Zuffa's method involves the identification of each grain type and an interpretation as to whether it is intrabasinal or extrabasinal. The papers of Zuffa (1985, 1987, 1991) outline criteria by which extrabasinal and intrabasinal grains may be distinguished, based only on the descriptive characteristics of the grains, and independent of any other knowledge of the basin setting in which the sediments were deposited. The limitations of Zuffa's (1985, 1987, 1991) methods involve the difficulty, in some cases, in correctly assigning grain types to the appropriate category. Also, once a grain is assigned to the extrabasinal category, no further subdivisions exist. This is undesirable, as in many instances extrabasinal grains may be important in defining specific sources for turbidites.

The second approach is quantitative, and relies on point counting methods. Problems arising from the second approach include both the methodology for the collection of data, and the tectonic interpretation of the data once it is collected. Point

counting and the calculation of modal percentages of framework grains have long been employed as a means of characterising the grain population of a sandstone, hence paving the way for an interpretation of provenance and tectonic setting (e.g. Dickinson, 1970; Dickinson and Suczek, 1979; Dickinson and Valloni, 1980; Dickinson et al. 1983; Potter, 1984; Dickinson, 1990).

'Classical' point counting methods involved the simple identification of every fragment which landed under the cross-hairs (Ingersoll et al., 1984). Since the proportion of rock fragments and feldspars in particular is partly dependent on grain size, this led to difficulty in comparing results from different studies. Convention dictated that samples counted should be of medium grain size, but in many cases the grain size of the available suite of samples made this impossible.

Dickinson (1970) and Gazzi (1966) independently arrived at a method whereby only the individual crystal (whether isolated or part of a rock fragment) under the cross hair is counted if it is greater than sand size, and only aphanitic rock fragments are counted as rock fragments. This method and the 'classical' method were reviewed by Ingersoll et al. (1984) who concluded that use of the Gazzi-Dickinson method, as it is now called, largely eliminates the grain size effect. There has been some discussion since (e.g. Zuffa, 1987, 1991) regarding the loss of information, particularly with regard to plutonic rock fragments, which results from use of the Gazzi-Dickinson method. The interpretation of the data once collected has been equally controversial.

Dickinson and Suczek (1979), Dickinson et al. (1983), Dickinson (1985), and Ingersoll (1990), among others, produced diagrams based on parameters derived from

point count data, which allow sandstone suites derived from various different tectonic settings to be distinguished (see figure 4.5 for a reproduction of the diagrams of Dickinson et al. (1983)). Several criticisms of the use of these diagrams have been recorded, including the fact that carbonate grains, which provide useful provenance information, are excluded from the parameters, and that the tectonic setting of deposition of turbidites may be far removed from the setting of the source area (e.g. De Rosa et al., 1986). These objections to the method have been outlined by Mack (1984) and Velbel (1980, 1985).

This chapter will include a qualitative discussion of the framework grains of the Goose Tickle group and Lower Head Formation followed by a presentation of their modal framework percentages utilising the Gazzi-Dickinson point counting method.

4.2 QUALITATIVE PETROGRAPHY

Zuffa (1991) has characterised three different types of deep-sea arenites on the basis of their grain types:

A. Pure extrabasinal;

B. Pure intrabasinal;

C. Mixture of extrabasinal with intrabasinal grains.

Zuffa's (1991) type A arenites are derived from erosion of 'hinterland' rock units located on basin margins and are typically deposited in trenches and foreland basins. Based on the analysis of the tectonic setting of the Goose Tickle group and Lower Head Formation given in chapter 3, it appears that arenites of these units should most closely resemble

Zuffa's (1991) type A. The common amalgamation of beds of the Goose Tickle group and Lower Head Formation, suggests, however, that a minor intrabasinal source should be observed in the form of rip-up clasts.

In the interests of brevity, the fact that both units were discovered to be broadly petrographically similar will be utilised in the organisation of the discussion of qualitative petrography. General textural and diagenetic features will be described in order to characterise the level of alteration of framework grains in each unit. The main framework grain types characteristic of both units are summarised in tables 4.1, 4.2, 4.3. and 4.4, and will be discussed with reference to these tables. Specific or unique characteristics of each unit will be described separately. Finally, the likely provenance of each grain type will be assessed and the constituent grains for each formation evaluated as extra- or intrabasinal in terms of Zuffa's (1991) approach. In this chapter, no further attempt will be made to relate the grain types to an actual source. Chapter 6 will discuss in more detail the hinterland areas as possible sources of detritus to the western Newfoundland foreland basin.

4.2.1 General Textural Features

The grain size of sandstones in the American Tickle formation varies from fine to very coarse sand and granule conglomerate. These sandstones are generally poorly sorted, and rounding of the grains is variable depending on their type (see tables 4.1, 4.2, 4.3, and 4.4). Grains are generally floating in the matrix, and although there is evidence of compaction in soft grains such as shale chips and detrital clay minerals, there

Table 4.1: Quartz and feldspar grain types in the Goose Tickle group and Lower Head Formation.

Quartz	
Type 1.	Monocrystalline quartz with slightly undulose extinction. Trails of vacuoles common. A small proportion of the grains contain needle-like inclusions. Well rounded to angular. Variable grain size.
Type 2.	Polycrystalline quartz, commonly with eight to twenty subgrains, which are usually equant, and have straight subgrain boundaries. Variable grain size, but commonly larger than the mean grain size. Subangular - rounded.
Type 3.	Euhedral quartz, clear, with embayments.
Type 4.	Polycrystalline quartz with highly elongate subgrains.

Plagioclase feldspar	
Type 1.	Grains showing albite twinning, clear with indistinct edges. Smaller than mean grain size.
Type 2.	Grains commonly show Carlsbad twinning, and tend to be cloudy. The grains are subhedral and usually display a stubby lath shape. Mean grain size to larger than mean grain size.
Type 3.	Untwinned cloudy grains, with central areas of different composition to rims. Commonly partially sericitised.

Potassium feldspar	
Type 1.	Clear microcline. May be angular or rounded. Minor euhedral grains. Commonly partly altered to plagioclase. Variable grain size.
Type 2.	Perthite - usually untwinned, showing stringy perthitic features. Generally larger than mean grain size.
Type 3.	Rounded cloudy microcline with indistinct tartan twinning, may be related to type 3 plagioclase feldspars.

Table 4.2: Sedimentary and plutonic rock fragments in the Goose Tickle group and Lower Head Formation.

Sedimentary Rock Fragments

Type 1.	Shale - dark brown laminated organic rich shale chips, may contain scattered silt grains. Rounded or may have ragged ends. Commonly larger than the mean grain size but may also be smaller. Usually deformed and penetrated by surrounding harder grains.
Type 2.	Shale - light brown/green shale chips. Not noticeably laminated. Vary from mudstone with no obvious preferred orientation of clay minerals to material with a strong preferred orientation of birefringent clay minerals. Generally rounded. Variable grain size.
Type 3.	Siltstone - cemented by quartz overgrowths and with minor clay matrix. Commonly rich in small grains of plagioclase feldspar. Subrounded.
Type 4.	Siltstone - carbonate cemented. Subrounded.
Type 5.	Carbonate - indistinct grains of micrite. Well rounded.
Type 6.	Carbonate - sugary grains with an interlocking texture, ?sucrosic dolomite.
Type 7.	Carbonate - bioclastic limestone.
Type 8.	Carbonate - isolated concentric and radial ooids.
Type 9.	Carbonate - peloidal wackestone with micritic or microspar matrix.
Type 10.	Chert - pale green or red with poorly preserved radiolaria.
Type 11.	Quartzose sandstone with rounded quartz grains, cloudy feldspar and rounded clear microcline. Some of the plagioclase is partially sericitised, some is partly altered to carbonate.

Plutonic Rock Fragments

Type 1.	Chloritised serpentine. May be rounded, or deformed with ragged edges. Mafic.
Type 2.	Grains showing graphic intergrowths of quartz and cloudy plagioclase. May contain patches of chlorite. Generally larger than mean grain size. Felsic.
Type 3.	Cloudy equigranular plagioclase feldspar, polycrystalline quartz, some chlorite. Felsic.
Type 4.	Polycrystalline potassium feldspar. Felsic.
Type 5.	Polycrystalline quartz with minor amount of clay. Felsic.
Type 6.	Polycrystalline quartz with cloudy untwinned plagioclase intergrowth. Felsic.
Type 7.	Plagioclase/microcline intergrowth. Felsic.
Type 8.	Microcline and polycrystalline quartz with inclusions, rounded. Felsic.
Type 9.	Coarse grained plagioclase aggregate. Felsic.

Table 4.3: Volcanic rock fragments in the Goose Tickle group and Lower Head Formation.

Volcanic Rock Fragments

Type 1.	Indistinct sheaves of feldspar in an opaque matrix. Variolitic texture. Mafic.
Type 2.	Intergrown indistinct plagioclase laths in a chlorite groundmass. Scattered opaques commonly visible. May display trachytic texture. Rare pyroxene and quartz in the groundmass. Mafic.
Type 3.	Featureless black opaque material with minor chlorite. ? Mafic.
Type 4.	Equant granular crystalline aggregate of cloudy silica. May contain brownish alteration patches and/or quartz phenocrysts. Felsic.
Type 5.	Quartz/plagioclase aggregate with chlorite groundmass. Felsic.
Type 6.	Aphanitic with disseminated opaques, very fine grained siliceous material in groundmass, and silica spherules. Felsic.
Type 7.	Brown volcanic glassy material, may be amorphous or have a 'brushed' spherulitic texture. ? Felsic.
Type 8.	Quartz and plagioclase phenocrysts in a dark glassy groundmass (porphyritic rhyolite). May contain faint microliths. Felsic.
Type 9.	Randomly oriented, poorly defined laths of plagioclase in groundmass, with phenocrysts of plagioclase. At least one has been veined prior to erosion. May contain some biotite. Intermediate.
Type 10.	Cloudy plagioclase feldspar showing spherulites and quartz phenocrysts with resorption textures. Felsic.
Type 11.	Grey-green cloudy microcrystalline quartz or feldspar. Radially arranged around carbonate spherulitic features. Patches of microcrystalline quartz. Plagioclase laths are visible in places. Felsic.
Type 12.	Grey-green volcanic composed of microcrystalline quartz or feldspar, quartz phenocrysts, and plagioclase which may be phenocrysts altered to carbonate. Felsic.
Type 13.	Plagioclase laths in sheaves with quartz microphenocrysts and disseminated opaques. Felsic.
Type 14.	Fresh looking plagioclase microphenocrysts in microcrystalline groundmass with radiating chlorite around carbonate spherules. Intermediate.
Type 15.	Polycrystalline quartz ± chlorite groundmass with small plagioclase phenocrysts. Felsic.

Table 4.4: Metamorphic rock fragments and accessory minerals in the Goose Tickle group and Lower Head Formation.

Metamorphic Rock Fragments	
Type 1.	Elongate grains, with strongly preferred orientation of birefringent clay minerals, whose crystal size is visible at the scale of point counting.
Type 2.	Polycrystalline quartz with elongate subgrains.
Type 3.	Quartz-mica aggregate with oriented micas.

Accessory minerals	
Type 1.	Glauconite- rounded, detrital
Type 2.	Zircon- rounded or subhedral
Type 3.	Garnet- commonly cracked and altered to calcite around the rims.
Type 4.	Chlorite- rounded, detrital, may be compacted, some have textures resembling chlorite amygdules.
Type 5.	Chromite- angular, brown transclucent, unaltered, commonly cracked.
Type 6.	Carbonate - distinct rounded grains of sparry calcite. Commonly larger than mean grain size. May be an alteration product of an unstable grain.
Type 7.	Monazite
Type 8.	Opaques
Type 9.	Mica- brown and green biotite
Type 10.	Rutile
Type 11.	Amphibole
Type 12.	Sphene - euhedral
Type 13.	Sphalerite
Type 14.	Calcite
Type 15.	Apatite - rounded
Type 16.	Pentlandite

is no evidence of sutured contacts or pressure solution between quartz grains (plate 4.1). The amount of matrix is high, and the sandstones are texturally immature; however, it is possible that the percentage of matrix in many cases has been overestimated. This is because the abundant shale chips act as pseudomatrix (Dickinson, 1970) and because many 'patches' of chlorite may in fact be altered plutonic or volcanic rock fragments. The matrix in these sandstones is predominantly chlorite, but also contains small grains of quartz and feldspar.

In some samples there is evidence of a highly birefringent microcrystalline clay mineral (?illite) forming rims around some of the quartz grains, although this is not common. The indistinct edges of most quartz grains are ascribed to a minor amount of early quartz overgrowth (plate 4.2), without prior formation of clay rims, and some possible corrosion or minor replacement by calcite. These incipient quartz overgrowth features are less common where shale chips and shale pseudomatrix are more abundant. A later, patchy, pore-filling sparry calcite cement is common in all samples. In some samples exfoliation textures are observed, where cracks in framework grains are filled with calcite. In many cases calcite cement is spatially associated with carbonate rock fragments and appears to have resulted from partial dissolution of these grains.

In several instances, particularly in fine grained samples, calcite has replaced framework grains, particularly feldspars, but also chloritised serpentine and quartz. The American Tickle formation is generally more altered than the Mainland formation (see below), particularly in samples from the Hare Bay and Pistolet Bay areas, where the percentage of carbonate cement is higher, and the degree of replacement of framework

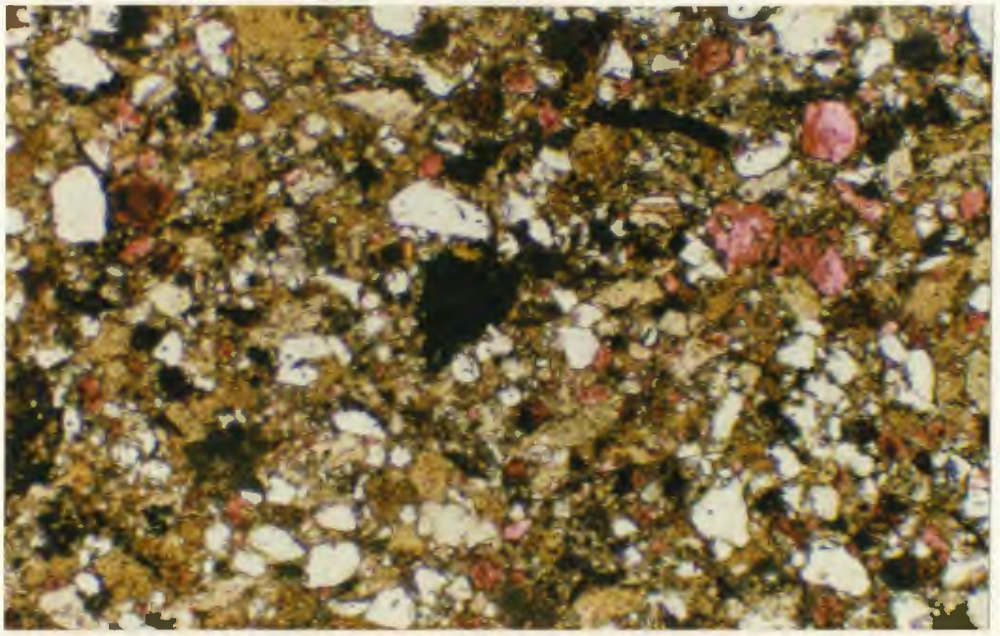


Plate 4.1: General appearance of the American Tickle formation in thin section. Pink grains are stained plagioclase feldspar. Note abundance of shale fragments. Plane polarised light. X32.

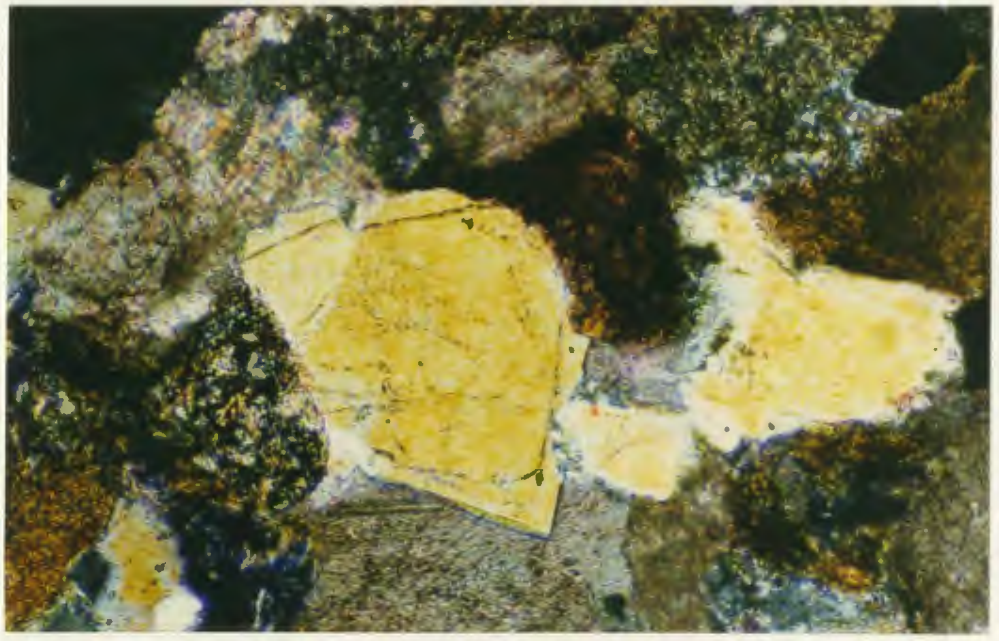


Plate 4.2: Euhedral early quartz overgrowth, followed by later sparry cement. American Tickle formation. Crossed polars. X32.

grains by carbonate is greater. Albite overgrowths on plagioclase feldspar are also observed in samples from these areas, and the grains are commonly flattened parallel to the regional cleavage.

The Mainland formation is broadly similar to the American Tickle formation in all the respects described above, although it has a lower degree of alteration, and carbonate cement is much less abundant. Some shale chips in the Mainland formation have been partly silicified around their edges, accounting for the fact that their central parts frequently weather out in the field. One sample, from near the top of the unit, contains abundant replacive calcite and authigenic k-feldspar overgrowths are observed on rounded microclines. This feature was only seen in one sample, and may have resulted from enhanced alteration along a fault zone.

Sandstones of the Lower Head Formation vary in grain size from medium-grained to very coarse-grained. Granule conglomerates are common. The sandstones tend to be poorly to very poorly sorted, with the poorest sorting in sandstones of the coarsest average grain size. The matrix is mostly chlorite, with patchy carbonate cement which is more abundant in concretions and fluid escape features. Indistinct edges on some quartz grains indicate a minor phase of early quartz overgrowth, similar to that observed in sandstones of the Goose Tickle group. As with the two formations described above, no evidence of pressure solution of quartz was observed. Some feldspars are strongly sericitised, some are partly altered to calcite. Some of the coarser samples show a high degree of calcite cementation and replacement by calcite. In one case complete outlines of relict feldspars are visible in the calcite cement.

For all formations bulk X-Ray Diffraction (XRD) analysis of selected samples (data not provided) indicates mainly quartz, albite, some microcline, and chlorite. The chlorite shows only a 7 angstrom peak, which, on the basis that many grains within the samples were optically identified as serpentine, was ascribed to the presence of serpentine. In light of the discovery that the 'serpentine' grains were, in fact, chlorite, it appears that the chlorite identified through XRD may be authigenic. Authigenic chlorite may display only a 7 angstrom peak, in contrast with more stable metamorphic chlorites which display a 14 angstrom peak; 7 angstrom chlorites, which were interpreted as authigenic, have been found in sandstones by Humphreys et al. (1989). Without further XRD and probe analyses, however, the origin of the 7 angstrom peak in these samples cannot be resolved.

The relatively low degree of alteration of the Mainland and Lower Head formations is consistent with information provided by Nowlan and Barnes (1987) who summarised available information on conodont colour alteration indices (CAI) for rocks of various ages in the Canadian Appalachians. In the case of the Port au Port Peninsula, where the Mainland formation is located (appendix 1, location map 1), the CAI for Middle Ordovician rocks is given as 1, corresponding to a temperature of 50 - 80°C. For the area north of Bonne Bay (appendix 1, location map 3) the CAI is given as between 1.5 and 2 reflecting temperatures of 50 - 140°C. In the Hare Bay area, the CAI is much higher, up to 5.5, indicating temperatures of up to 400°C, which is consistent with the much higher degree of alteration seen in samples from these areas.

4.2.2 Framework Grains - General Description

In the following discussion grain 'type' refers to the categorisation of grain types given in tables 4.1, 4.2, 4.3, and 4.4. The American Tickle, Mainland, and Lower Head formations all contain examples of all the types of quartz and feldspar grains referred to in table 4.1. They vary somewhat in the types of rock fragments displayed (tables 4.2, 4.3, and 4.4).

The American Tickle formation contains sedimentary rock fragments of all types except 6, 10, and 11. Varieties of shale and siltstone are the most abundant types of sedimentary rock fragment. A very minor proportion of the type 8 ooid grains are chamositic, reaching 1mm in size. Plutonic fragments are dominated by type 1 chloritised serpentine, with lesser amounts of types 2 and 3 (felsic). Volcanic fragments are present in varying proportions and include types 1, 2, and 3 (all mafic) and 4, 5, and 7 (felsic). Metamorphic rock fragments in the American Tickle formation are uncommon, and mainly consist of type 2 phyllite grains. Accessory minerals include all types except 11 (amphibole). Type 14 grains of sparry polycrystalline calcite appear detrital, but are interpreted as altered grains of other minerals.

The Mainland formation contains abundant shale chips of type 1 and 2 among its sedimentary rock fragments. Types 3 and 4 (siltstone) and types 5, 6, 7, 8, and 9 (various types of carbonate grains), are also present, with type 8 also including minor chamositic ooids. Plutonic fragments include type 1 chloritised serpentine, as well as 2, 4, and 6 (felsic). Volcanic rocks in the Mainland formation are predominantly of type 2 (dominated by indistinct plagioclase laths - probably mafic) with lesser proportions of

types 4 and 10 (both felsic). Metamorphic types in the Mainland formation include all three types. Accessory minerals include all except 11 (amphibole) and 14 (calcite).

Comparison of the American Tickle formation with the Mainland formation shows that the two are petrographically similar in many respects. Slight differences are visible in that, particularly in the uppermost part of the Mainland formation, rock fragments of metamorphic origin are more prominent, although they are still not very abundant. Additionally, glauconite is also more prominent in the Mainland formation, although again it is not very abundant. The greater abundance of calcite grains in the American Tickle formation is interpreted to reflect the higher diagenetic grade of this unit - some detrital grains have been completely replaced by calcite.

The Lower Head Formation contains a great variety of sedimentary rock fragments which include all types. All types of plutonic rock fragments except type 9 are present and thus the Lower Head Formation contains a variety of felsic plutonic fragments as well as chloritised serpentine. The Lower Head Formation contains the entire range of volcanic rock fragments from type 1 to 18 which include a variety of compositions ranging from mafic through intermediate to felsic. The suite of accessory minerals is more restricted than in the Goose Tickle group and includes types 2, 4. 5, 6, 7, 8 and 14. Type 14 calcite is again interpreted as altered detrital grains. The Lower Head Formation, while it is broadly similar to the Goose Tickle group petrographically, contains a greater variety of all types of rock fragments. The greatest variety of rock fragments, particularly volcanic and plutonic rock fragments, is seen in coarse granule sandstones, which are associated with facies LH1 (see chapter 3).

4.2.3 Framework Grains - Individual

4.2.3.1 Quartz

Type 1 quartz generally displays straight to slightly undulose extinction, and is inclusion-free, although a small proportion of the grains contain needle-like inclusions, probably of rutile. None of the inclusions were diagnostic of a particular source, and therefore have limited value in provenance determination (Boggs, 1992). Many of the quartz grains contain trains of vacuoles, which, however, are also of limited value in provenance determination (Boggs, 1992). The grains vary from very well rounded to angular. Abraded overgrowths are almost never seen. Strain features (Bohm lamellae) are seen in some quartz grains of this type. Many are unrelated to any sedimentological feature, and are interpreted as having been generated by strain incurred prior to the incorporation of the quartz grain into the sediment. A small number of samples contain Bohm lamellae which are seen radiating from the contacts between two quartz grains, and are therefore interpreted as a diagenetic compaction feature.

The equant subgrains and straight subgrain boundaries of the polycrystalline quartz grains (type 2) are suggestive of a high grade metamorphic or plutonic source (Young, 1976).

Types 3 and 4 quartz are very uncommon in all formations. Type 3 clearly indicates a volcanic source, whereas type 4 is indicative of a metamorphic source.

4.2.3.2 Plagioclase Feldspars

Grain edges and cleavage planes on type 1 plagioclase feldspars of all three

formations are commonly altered to sericite and calcite. Type 1 plagioclase feldspars show albite twinning and tend to be less cloudy than other varieties. Type 2 plagioclase feldspars are unzoned, and have a variety of shapes, from equant to stubby laths which may show Carlsbad twinning. The majority of plagioclase feldspars (type 3), however, are untwinned. Most plagioclase feldspars are dark under cathode luminescence, suggesting that they may have undergone alteration at low temperature (Kastner, 1971). This does not necessarily imply that they underwent albitisation in the Goose Tickle group and Lower Head Formation.

Some grains which are apparently of potassium feldspar show complex internal structures which are visible on stained samples, under cathode luminescence and in the backscattering mode of the SEM. Many show cores or internal patches of albite, which may mimic the external grain shape. This suggests that at least some of the grains were originally albite and have been altered to potassium feldspar, and thus they should be categorised as type 3 plagioclase feldspars. It is clear in some cases that alteration of albite to potassium feldspar has taken place along cleavage planes, supporting this hypothesis.

Zoning is never observed in plagioclase feldspars from the Lower Head Formation and Goose Tickle group. The presence of oscillatory zoning in plagioclase feldspars of sand size is commonly taken as indicating derivation from a volcanic or hypabyssal source (Pittman, 1963; Lundberg, 1991); however, unzoned feldspars can occur in many volcanic rocks (Boggs, 1992), so this is not conclusive evidence that the feldspars were derived from a plutonic or metamorphic source. Small laths, such as are typical in

volcanic rock fragments of all three formations, are almost never found as separate grains.

4.2.3.3 Potassium Feldspars

Apparently relatively unaltered, and in many cases very well rounded grains of microcline (type 1) are common. Under cathode luminescence these luminesce bright blue suggesting that they have a high grade metamorphic or plutonic origin. On staining, however, it is clear that many of these grains have a patchy texture, with the patches consisting of albite (plate 4.3). At first, the author suspected that this was an artifact of the staining method, but SEM and cathode luminescence studies as well as more careful optical,studies (plate 4.4) confirmed that these features are real. In certain cases, the patches appear to coalesce and the impression of an albite grain altered to microcline around its edges is given. If these two features are related, this would suggest that the 'patchy' textures of many microclines arise from relict albite, rather than representing an irregular 'blebby' perthite structure. In other cases, microcline grains have been partly altered around the edges to albite. True perthite (type 2) is also found in these samples and contains stringy blebs of albite in potassium feldspar.

A third type of feldspar (type 3) consists of rounded cloudy microcline with indistinct tartan twinning in some cases, and no twinning in others. This type again displays cores of albite (and was referred to above in the discussion of plagioclase feldspars), and commonly has an very altered appearance. The albite cores mimic the shape of the grain, and hence again this is interpreted as the incomplete alteration of

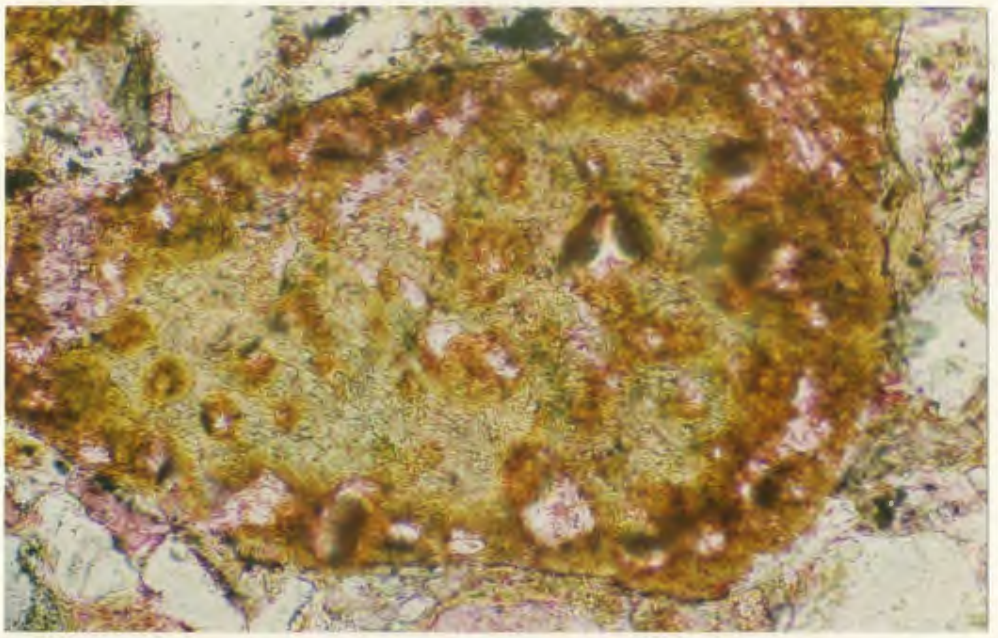


Plate 4.3: Potassium feldspar (yellow stain) showing typical 'patches' of albite (pink stain). Lower Head Formation. Plane polarised light. X310.

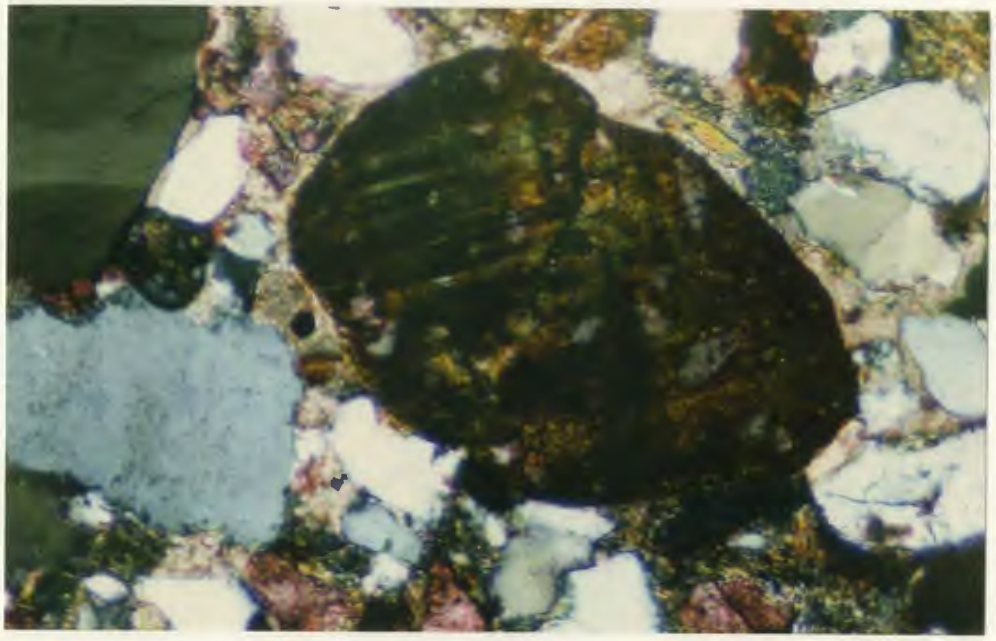


Plate 4.4: Rounded microcline displaying uneven extinction as a result of internal patches of albite. Lower Head Formation. Crossed Polars. X100.

albite to potassium feldspar. The cloudiness of this potassium feldspar resembles that described by Morad et al. (1989) for very low temperature authigenic potassium feldspars.

Since both cathode luminescence and electron microprobe (see below) evidence seems to suggest that most, if not all, of the potassium feldspar is of metamorphic or plutonic origin (figures 4.1, 4.2, 4.3), it would appear that the textures described above were not imparted while the grains were within the sediments of the Goose Tickle group and Lower Head Formation. The grains may have been incorporated with the alteration features already present.

However, in the mind of the author, this question is not completely resolved. The origin of albite in sandstones has been the topic of extensive discussion for several years (e.g. Saigal et al., 1988), and the question of whether these patches and cores could be the result of in situ albitisation should at least be considered. Saigal et al. (1988) suggested a number of criteria for the recognition of albitisation of detrital potassium feldspar grains;

1. Euhedral habit of albite crystals with sharp edges and corners and markedly smooth crystal faces;
2. Generally untwinned albitised grains mostly riddled with minute brownish inclusions;
3. Lack of cathode luminescence in albite;
4. Homogenous and pure albite composition (>99% Ab);
5. Absence of albitised grains in carbonate cemented zones;
6. Increase in the percentage and degree of albitised K-feldspar with depth.

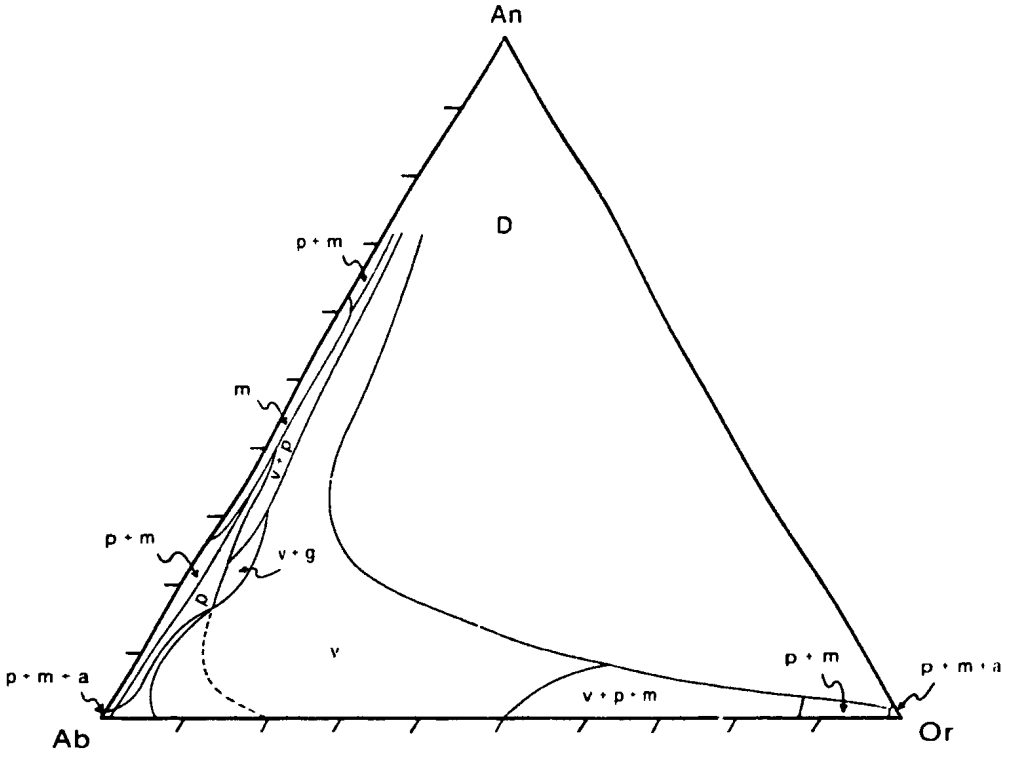


Figure 4.1: Feldspar discrimination diagram of Trevena and Nash (1981). v = volcanic; p = plutonic; m = metamorphic; v + g = volcanic or granophyre; v + p = volcanic or plutonic; v + p + m = volcanic or plutonic or metamorphic; p + m + a = plutonic, metamorphic or authigenic. Analyses to the left of the dashed line in the volcanic field represent uncommon low-temperature rhyolites of extreme composition.

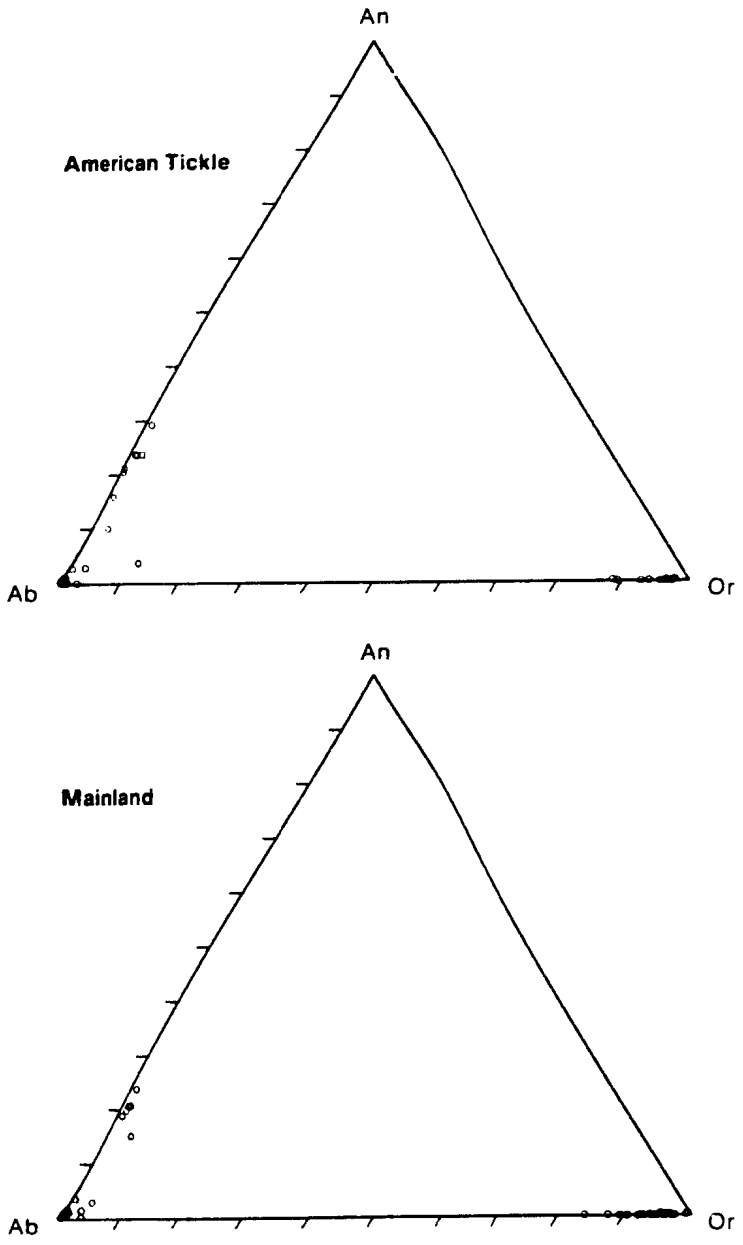


Figure 4.2: An-Ab-Or plot of feldspar compositions for the Mainland and American Tickle formations.

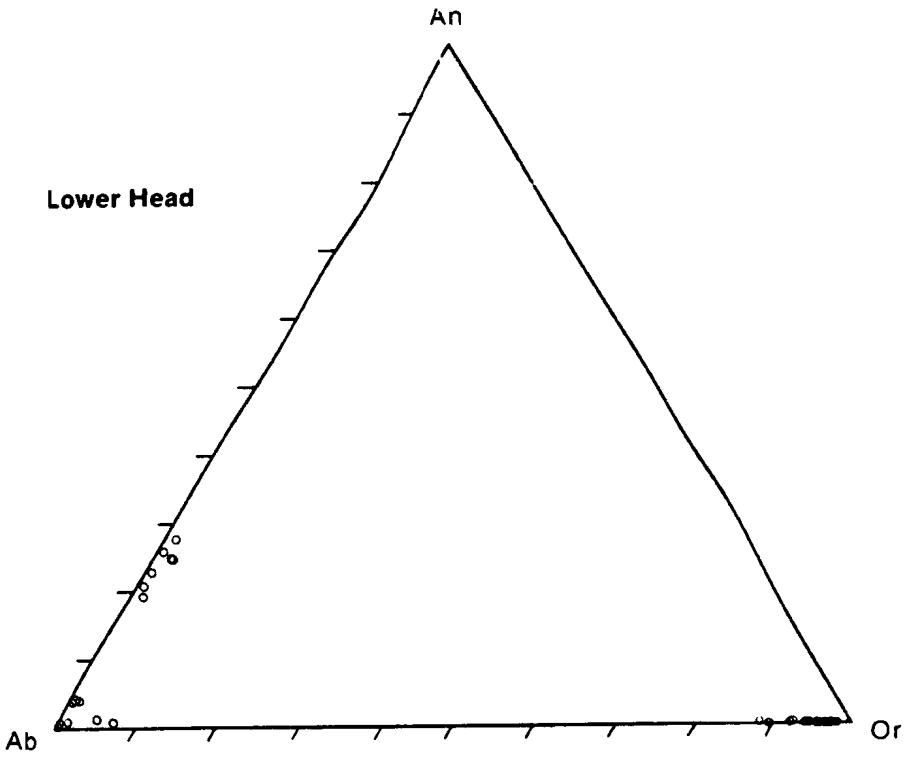


Figure 4.3: An-Ab-Or plot of feldspar compositions for the Lower Head Formation.

The crystal form described in point 1 was not observed, patches and cores have an irregular shape. Albite within the microclines is not noticeably more cloudy than the microcline itself, and twin planes in the microcline appear to cross the albite. The albite, however, is non-luminescing. Albite in altered patches was not probed, and so no comment can be made on the composition of the patches. In carbonate cemented zones, 'patchy' k-feldspars appeared to be as common as in non-carbonate cemented zones, and even in the most altered examples of the American Tickle formation, where albite overgrowths are present on plagioclase feldspars, relatively unaltered k-feldspar is still present.

Although Walker (1984) suggested that albitisation requires temperatures in excess of 100°C, the temperature range suggested by Saigal et al. (1988) for diagenetic albitisation of k-feldspar is 65-90°C for Type I albite, and >90°C for Type II albite. Type I albite consists of numerous tiny albite crystals growing along cleavage planes in the host grain, and is clearly not similar to the textures observed here. Type II albite consists of blocky crystals which tend to form pseudomorphs of the host grain. This bears a greater similarity to the observed features, and indeed Saigal et al. (1988) do suggest that alteration textures will resemble patches. The temperature range for type II albite is consistent with that inferred for diagenetic grades of the American Tickle and Lower Head formations, but is slightly above the temperature inferred for the Mainland formation from conodont colour alteration indices (Nowlan and Barnes, 1987).

Type II albitisation is the most likely type to have taken place where either a rim of albite is present, or other clear evidence exists that albite is the later phase. In the

majority of cases, the evidence is not conclusive in determining whether albite represents the original or secondary phase. In summary, possible explanations for observed textures are listed below.

1. Patchy texture in microclines:

    a) blebby perthite;

    b) type II albitisation of Saigal et al. (1988);

    c) incomplete alteration of earlier albite.

2. 'Albite core' texture in untwinned k-feldspar:

    a) incomplete alteration of earlier albite.

3. Alteration of albite to k-feldspar along cleavage planes:

    a) incomplete alteration of earlier albite.

Further studies of selected grains utilising the secondary electron mode of the SEM on chips and polished sections, cathode luminescence, and the electron microprobe are required to resolve this problem.

4.2.3.4 Feldspar Compositions

Compositions of both plagioclase and potassium feldspars for the Lower Head, Mainland and American Tickle formations are provided in appendix 3, sections, A3.8, A3.9, and A3.10. When plotted on Albite-Anorthite-Orthoclase diagrams and compared with typical compositions for detrital feldspars from a variety of sources (Trevena and Nash, 1981) (figure 4.1), all three formations show similar patterns (figures 4.2, 4.3). Plagioclase feldspars plot in two different fields, the first being close to the albite pole,

and the second corresponding to a field in the composition of oligoclase (An20 - An30). The first group falls into the field of plutonic, metamorphic and authigenic feldspars, and combining this information with information from cathode luminescence studies, it undoubtedly includes some feldspars which have experienced low temperature alteration; however, no distinction is possible between feldspars which have been albitised in the source rock, and those which were albitised in the present host rock.

The feldspars of the second group contain very little potassium, and thus they fall into the field of plagioclase feldspars with a metamorphic or plutonic provenance rather than those with a volcanic provenance. Thus the lack of zoning observed in plagioclase feldspars in this case may actually indicate derivation from a plutonic or metamorphic source.

Potassium feldspars contain significant but not large amounts of sodium and also fall into the field of feldspars derived from a plutonic or metamorphic source. They also typically contain significant proportions of Ba, which is typical, according to Van de Kamp and Leake (1985) of k-feldspars derived from a 'granitoid' source. Authigenic potassium feldspars are present in one sample of the Mainland formation, and these are very pure orthoclase, plotting at the orthoclase pole.

4.2.3.5 Sedimentary Rock Fragments

Shale chips (types 1 and 2) are the dominant sedimentary rock fragment in all three formations (plate 4.5). Dark, organic rich, well laminated shale chips are particularly abundant in the Goose Tickle group. Some of the dark shale chips show

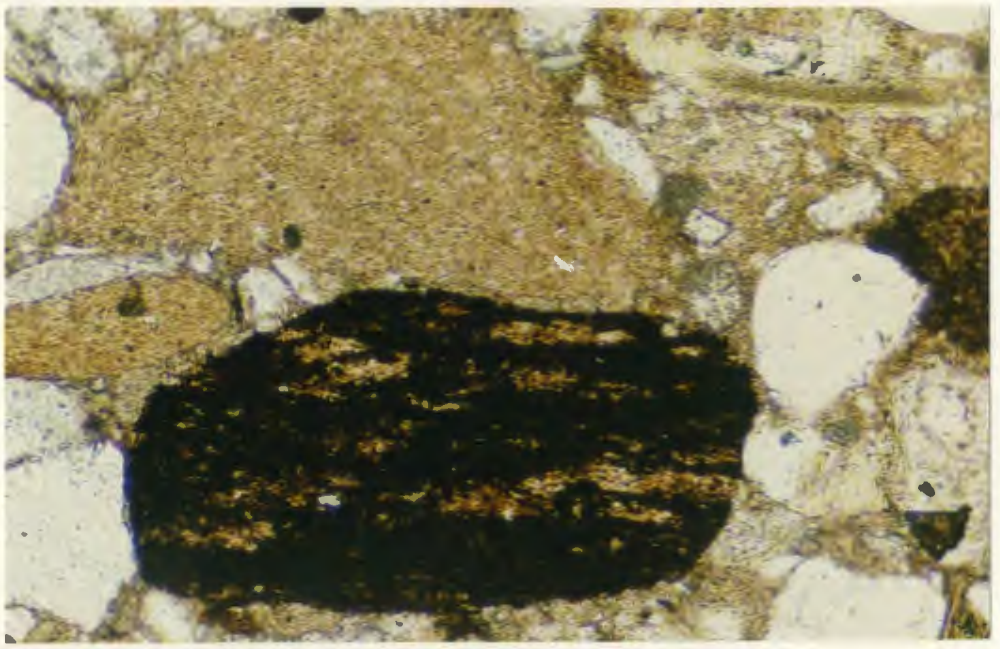


Plate 4.5: Two different types of shale chips in the American Tickle formation. Plane polarised light. X32.

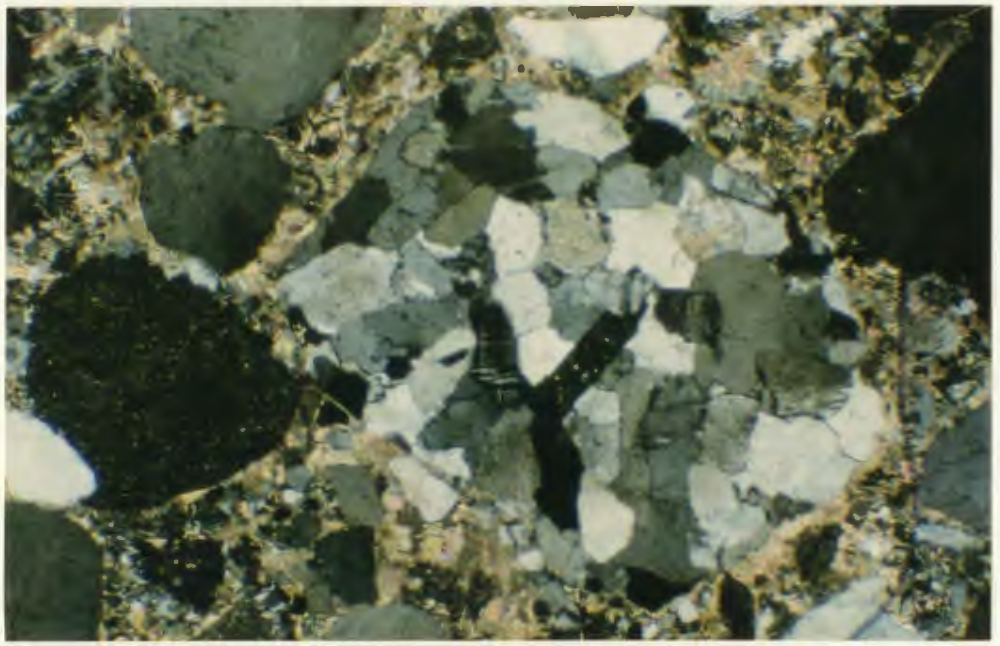


Plate 4.6: Quartz cemented sedimentary rock fragment from the Lower Head Formation. Crossed Polars. X32.

evidence of minor growth of authigenic dolomite. In one case, a pyrite nodule was observed which was detached from a shale chip, suggesting an origin for the fairly abundant framboidal pyrite within these samples. Clearly the laminated variety of shale chips have undergone significant compaction to form the organic rich laminae, prior to incorporation in the sandstones, hence they are not considered to be rip-up shale clasts, but material which has been eroded from a pre-existing basin floor. This is consistent with Zuffa's (1987) criteria for recognition of extrabasinal grains.

Generally speaking, carbonate grains are predominantly structureless micritic grains (type 5). All other types of carbonate grain are much less abundant, and tend to be associated with granule conglomerates in facies LH1 of the Lower Head Formation (see chapter 3). Sucrosic carbonate grains of type 7 tend to be stained with organic material in some samples, particularly in deformed and altered northern samples of the American Tickle formation. Some of the peloidal limestones (type 9) have a minor bioclastic component and may also contain scattered quartz grains. In almost all cases ooid fragments (type 8), which are present in the Mainland and American Tickle formations, are single ooids, implying that they were transported prior to cementation.

Some chert grains (type 10) are partly altered to carbonate. Some also contain spherulitic features which are probably radiolaria, and siliceous sponge spicules.

Subrounded sandstone fragments (type 11), which are quartz cemented, and contain well rounded quartz, microcline, and albitised plagioclase, are a minor but striking component of the Lower Head Formation (plate 4.6).

Recognition of grains as extrabasinal is most problematic with sedimentary grains,

as the faunal evidence referred to by Zuffa (1985) is not present and for most grain types textural features are not conclusive. Nevertheless, most sedimentary fragments are rounded, and it appears that the majority of sedimentary rock fragments are extrabasinal, with the possible exception of some of the unlaminated shale chips.

4.2 3.6 Plutonic Rock Fragments

Type 1 grains were optically identified as serpentine on the basis of several features, i.e. low birefringence, pale green colour in plane polarised light, mesh textures, and the fact that they contain possible calcite pseudomorphs after pyroxene. In some samples, grains identified as serpentine are altered to quartz and carbonate. This is reminiscent of a typical low temperature metamorphic reaction of serpentine (Winkler, 1979; Springer, pers. comm. 1990) in which serpentine is altered to quartz and magnesite; however, SEM work showed that the carbonate surrounding the grains was simple calcite. In samples from both the American Tickle and Lower Head formations, chromite was observed to be associated with the grains, a typical ultramafic association supporting their identification as serpentine (plates 4.7, 4.8). In one of these samples red-brown chromite has an opaque rim. Around the chromite is an alteration halo of translucent non-pleochroic mineral. According to R.K. Springer, (1991, pers. comm.) - the opaque edges of the chromite grains are probably magnetite, and the aluminium which was released from the chromite has altered the serpentine to chlorite. This is a typical alteration sequence in ultramafic rocks and probably occurred before the serpentine became a rock fragment. A possible serpentine conglomerate or plutonic

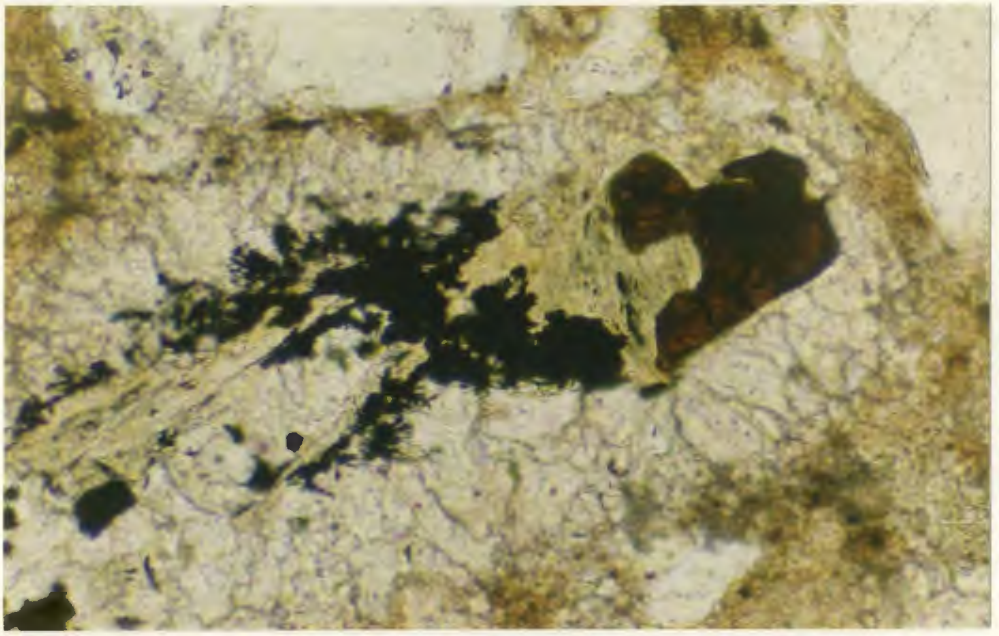


Plate 4.7: Chromite in serpentine grain which has been altered around the margins to calcite. American Tickle formation. Plane polarised light. X310.

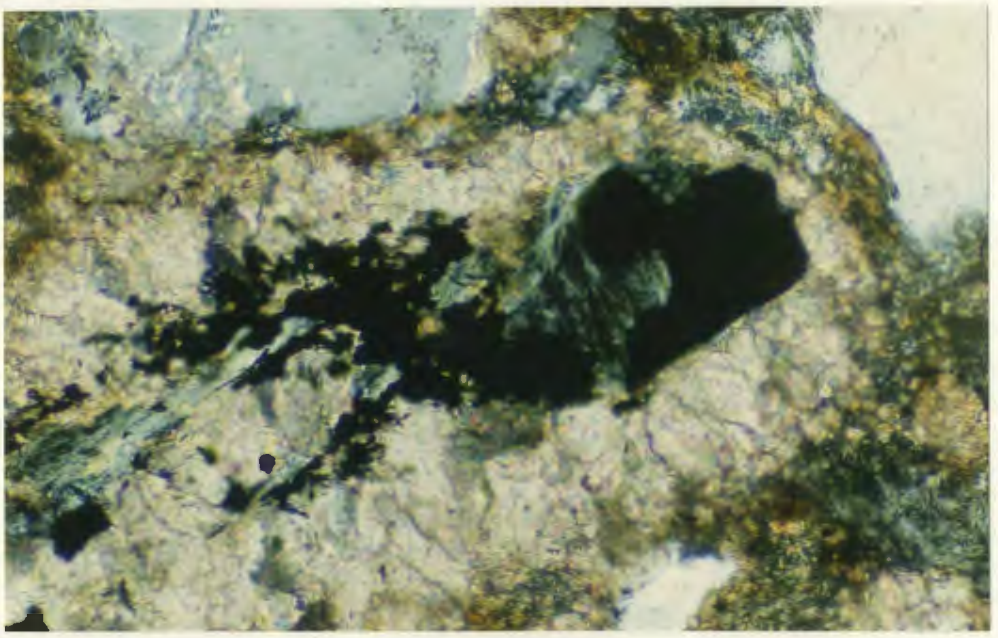


Plate 4.8: Same view as above. Crossed polars.

breccia was also observed, composed of angular fragments of serpentine. Individual serpentine grains, and serpentine breccia, may contain scattered opaque minerals, probably magnetite or chromite.

An attempt was made to confirm the optical identification of serpentine grains using electron microprobe analyses. This proved unsuccessful, partly because the soft centres of the grains were removed by the polishing process, but mostly because in all cases grains optically identified as serpentine turned out to be composed of chlorite. The variation in hardness from the interior to the exterior of the grains suggests that a chemical reaction has taken place which has altered the grain edges more than the interiors (see plates 4.9, 4.10). This could have occurred while the serpentine grain was in the area where it was originally eroded, or it could have occurred as a diagenetic reaction within the Goose Tickle group and Lower Head Formation. The hypothesis that composition varies from the centres of the grains to the edges is supported by probe analyses and subsequent qualitative investigations using the SEM, which demonstrated that the edges of the grains are generally richer in aluminium and iron relative to magnesium, in comparison with the interiors of the grains which are richer in magnesium relative to aluminium.

Henceforth the grains of serpentine will be referred to as 'chloritised serpentine'. Chloritised serpentines in both the Goose Tickle group and the Lower Head Formation contain small but significant proportions of Cr and Ni (appendix 3, sections A3.1 and A3.3). Grains from the Goose Tickle group show the highest values of Cr and Ni. Typically, Cr and Ni are rarely analysed in chlorites which are not independently known

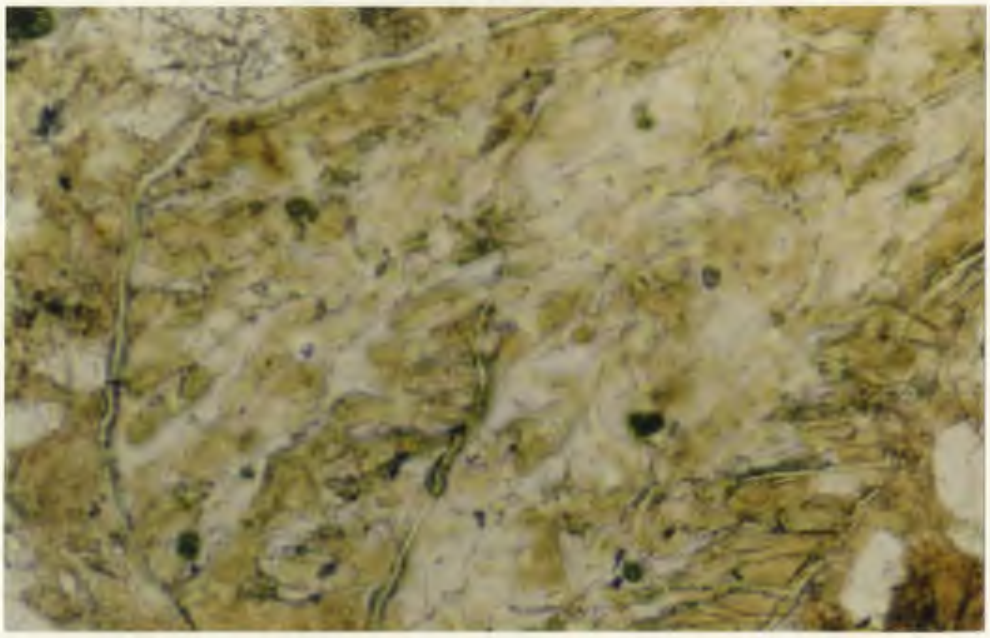


Plate 4.9: Chloritised serpentine grain. Lower Head Formation. Plane polarised light. X32.

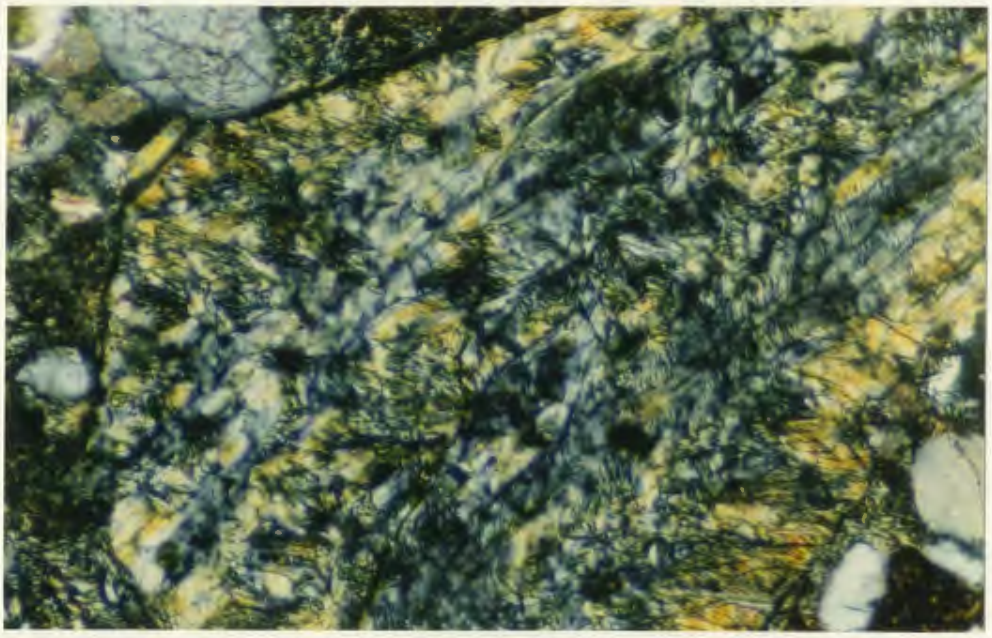


Plate 4.10: Same view as above in crossed polars. Note apparently different composition of grain edges and grain interior.

to have been derived from ultramafic rocks (Laird, 1988), but 'significant' proportions of Cr and Ni are present in chlorites derived from metamorphism of ultramafic rocks (Laird, 1988). Matzat and Shiraki (1972) quote Zeissink (1969) as having identified chromian chlorites to be weathering products of ultramafic rocks, but analyses of chromian chlorites provided in Bailey (1988) contain weight percent proportions of Cr_2O_3 varying from 3.16% to 9%, far greater than those observed in the Lower Head Formation and Goose Tickle group. Bailey (1988) also presented one analysis of a more typical clinochlore (nomenclature according to AIPEA recommendations, 1980) which contains 0.03% Cr_2O_3. The maximum proportion of Cr_2O_3 which occurs in chloritised serpentines of the American Tickle formation is 0.584%. Thus the Cr proportion appears to be higher than in 'average' chlorites, but lower than in chromian chlorites.

The maximum abundance of nickel in the American Tickle chlorites is 0.283%. This is comparable to nickel values quoted by Bailey (1988) for chromian chlorites. Burns et al. (1974) quoted typical values of Ni in chlorites from mafic igneous rocks as ranging from 150 to 1200 ppm. Nickel values for chlorite derived from metamorphic rocks are also given by Burns et al. (1974) and range from 45 to 210 ppm. Therefore the proportion of Ni in American Tickle serpentinised chlorites is higher than for 'average' chlorites.

If higher than average Cr and Ni values are characteristic only of altered serpentines, other detrital grains identified optically as chlorite, and chlorite interstitial to plagioclase laths in volcanic fragments might have notably different proportions of Cr and Ni. Some of these types of grains were also probed but the results proved

inconclusive as some of these types of chlorite also contain significant amounts of Cr and Ni.

There is no obvious correlation between the behaviour of Cr and Ni in chloritised serpentines. Some grains are rich in Cr, others are rich in Ni, still others are rich in both. There is also no apparent correlation between these two parameters and the Mg content of the chlorites. Thus the Cr and Ni values recorded for chloritised serpentines cannot be regarded as conclusive proof of an ultramafic origin, and the best evidence remains the textural evidence described above.

Little information is available on the behaviour of serpentine as a sedimentary rock fragment (Nichols et al., 1991) and even less is available about its behaviour during diagenesis. Much more is known about metamorphism of ultramafic rocks, and Tracy and Frost (1991) stated that under conditions up to the highest grades of hornblende hornfels facies, chlorite is the major aluminous mineral in metaperidotites (i.e. the major alteration product of serpentine). Tracy and Frost (1991) further suggested that the aluminium content of chlorites in metaperidotites should increase with increasing metamorphic grade. Aluminium contents of chloritised serpentines of the Goose Tickle group and Lower Head Formation fall within the fields indicated by Laird (1988) for metamorphic chlorites (figure 4.4), suggesting that the bulk of the alteration may have taken place prior to incorporation in the sediment.

In addition to large grains identified as serpentine, some smaller grains of phyllosilicate, and some which were interstitial to feldspar laths in volcanic rock fragments were probed, particularly for the Lower Head Formation. The difference in

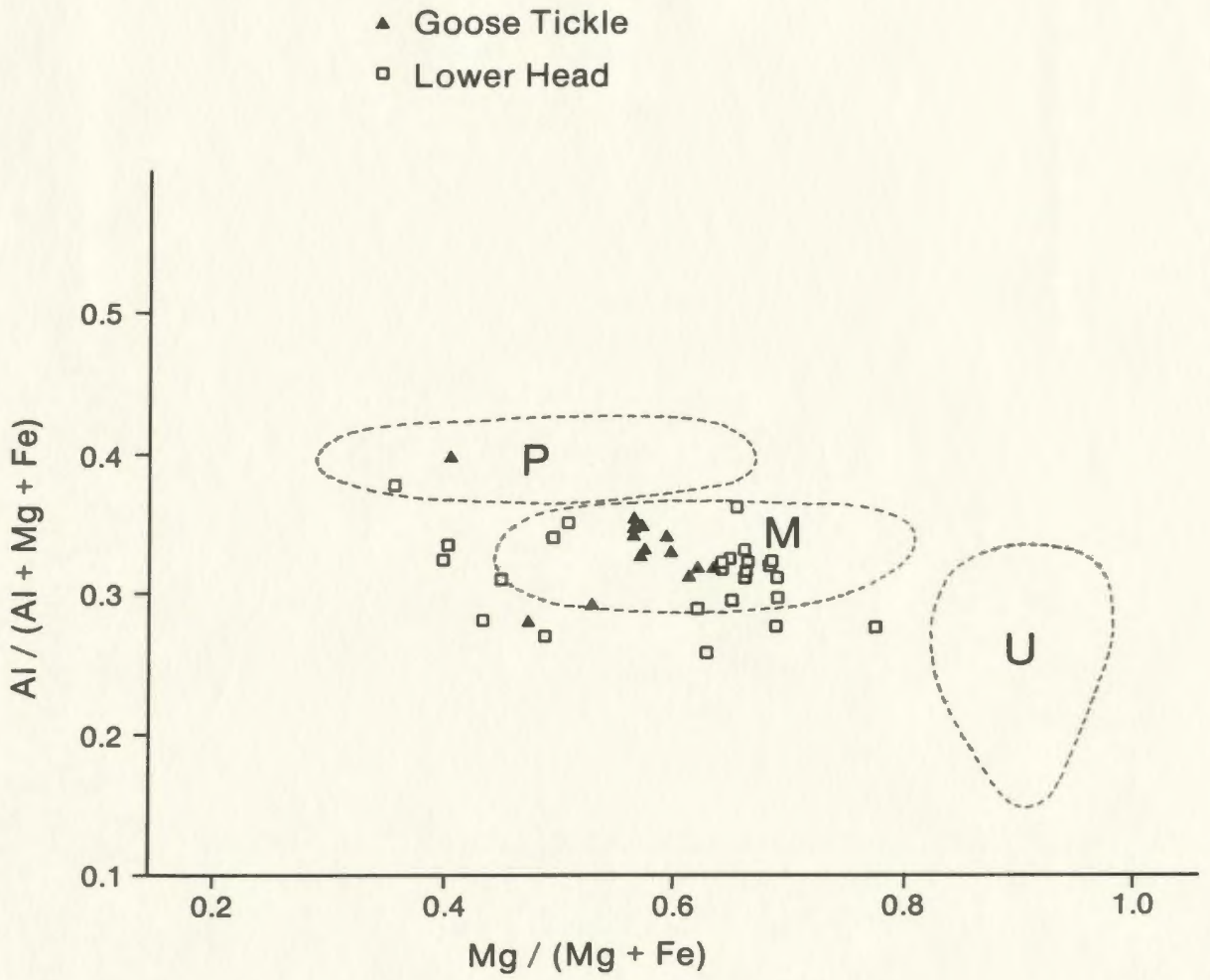


Figure 4.4: Plot of Al/(Al+Fe+Mg) vs. Mg/(Fe+Mg) for chlorites, Goose Tickle group and Lower Head Formation. U indicates the field for ultramafic chlorites; M - metamorphic chlorites; P - chlorites derived from pelites. Fields from Laird (1988).

composition is clear from figure 4.4. The small interstitial chlorites fall to the left of the mafic field, and some intersect with the area of felsic rocks as indicated by Laird (1988) (not shown on the diagram). In addition, although chloritised serpentines from the Lower Head Formation are more Mg rich than those from the Goose Tickle group, none of the chlorites fall into the field typical of metamorphosed ultramafic rocks. This would imply that alteration of the serpentine involved considerable gain in aluminium and iron, and consequent loss of magnesium.

It is suggested that the alteration may have taken place in a sedimentary or other unusual setting, in which there would be expected to be a greater supply of aluminium from other detrital grains, than would be expected in a pure ultramafic rock which was subjected to metamorphism. It is also suggested that the degree of alteration of serpentines in the Lower Head Formation was not as great as for those in the Goose Tickle group, given the higher magnesium contents of these grains. This is supported by the generally lower Ni and Cr contents in chloritised serpentines of the Lower Head Formation, which implies less breakdown of pyroxenes (Ni) and chromites (Cr) in the host rock.

In some samples, detrital phyllosilicate grains, again texturally similar to serpentine, are composed of a mineral of moderate relief, which has a platy habit, a well developed cleavage, is pale brown or green in plane polarised light, and characteristically displays second order birefringence colours. This has tentatively been identified as vermiculite. Some chloritised serpentine grains have apparently been recrystallised around their edges to a clay mineral which is macrocrystalline, and has a birefringence

too high for most forms of chlorite, and too low for most forms of mica and talc. This may also be vermiculite, which does occur as an alteration product of chlorite (Chamley, 1989).

Vermiculite is known to occur in association with ultramafic rocks, although it has mainly been described in ultramafic rocks which have been intruded by pegmatites (De la Calle and Suquet, 1988). According to Deer, Howie and Zussman (1966) vermiculite forms at temperatures less than 300 degrees, and it is here suggested that at least some of the vermiculite, particularly that which rims detrital grains, may have formed in the diagenetic environment. It is also possible that these more highly birefringent clay minerals are mixed layer clays such as those recorded by Bettison and Schiffman (1988) in ophiolitic rocks from California. It should be noted, however, that no evidence for either vermiculite or mixed layer clays has yet been encountered during electron microprobe or scanning electron microscope studies.

By no means all isolated phyllosilicate grains are altered serpentine. Some chlorite grains are probably derived from volcanic fragments ranging from mafic to felsic, since several were observed to be attached to plagioclase phenocrysts. However, it is believed that the vast majority of sand-sized phyllosilicate grains (>95%) were originally serpentine.

Most other plutonic fragments were found in the Lower Head Formation granule conglomerates. A typical example of a type 2 plutonic fragment is shown in plate 4.11. Type 6 grains are aggregates of very large Carlsbad twinned, slightly sericitised feldspars. Type 8 grains were only seen in one sample. In all units it is unusual to find

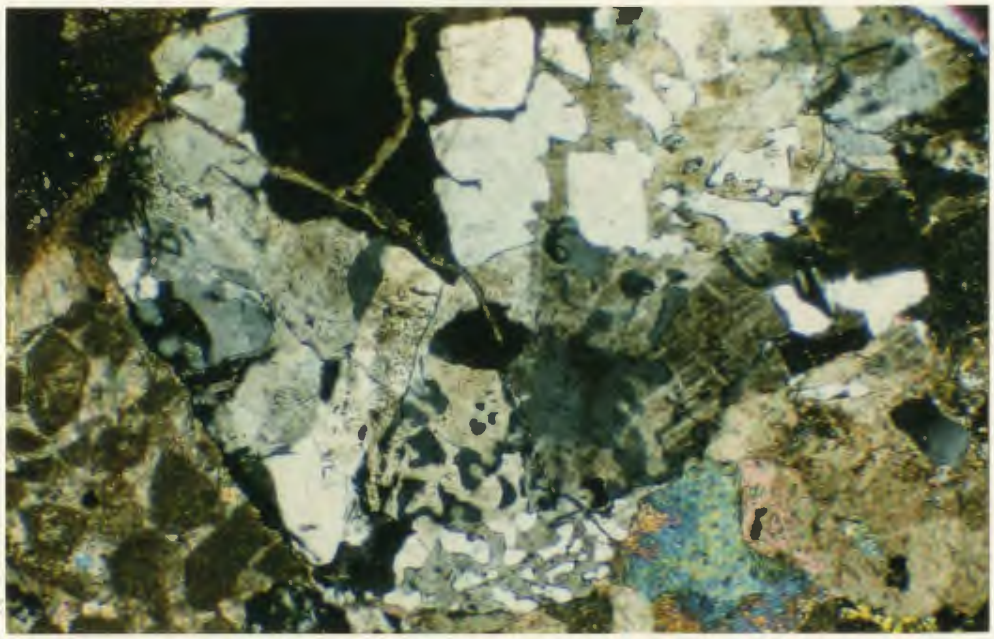


Plate 4.11: Graphic intergrowth of quartz and plagioclase. Felsic rock fragment. Lower Head Formation. X32.

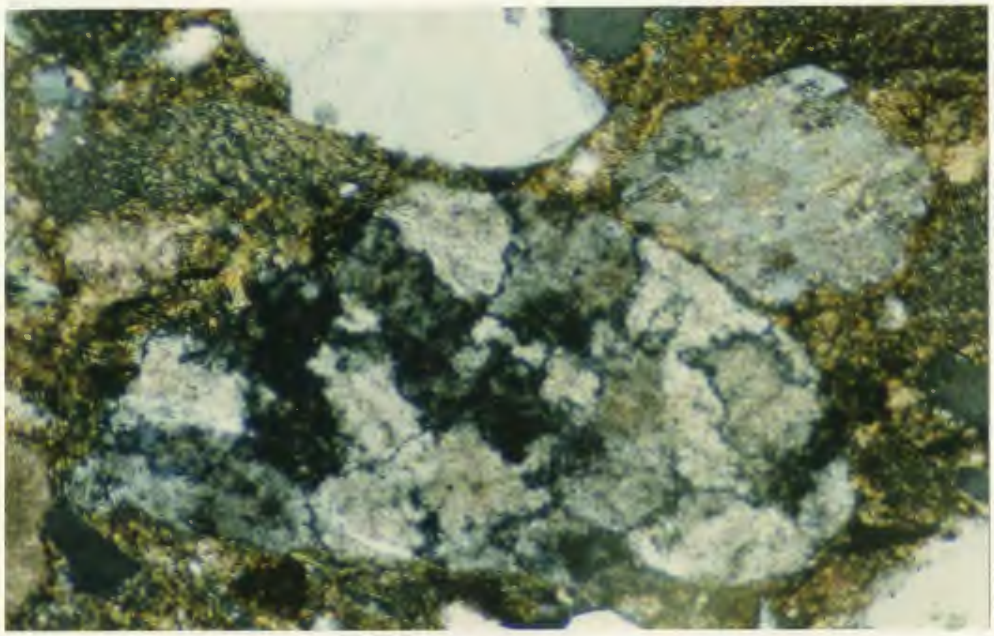


Plate 4.12: Murky felsic volcanic rock fragment. American Tickle formation. Crossed polars. X100.

potassium feldspar in rock fragments, which are dominated by plagioclase.

Since syndepositional plutonic rocks are never exposed, all plutonic fragments are considered to be extrabasinal.

4.2.3.7 Volcanic Rock Fragments

Several of the rock fragments which were interpreted as felsic (e.g. plate 4.12) contain quartz phenocrysts, and the presence of spherulitic textures, which are typical of devitrified rhyodacite rocks, is consistent with an identification of the fragments as rhyolite or dacite (R.K. Springer, pers. comm. 1991).

One example of a type 2 volcanic fragment was examined using the backscatter feature of the Scanning Electron Microscope and was found to contain laths of albite, in a groundmass of chlorite. Small amounts of quartz and pyroxene with a composition most resembling augite were also found in the groundmass. Intermediate to mafic volcanic fragments commonly have textures which vary from microlithic (plate 4.13) to lathwork with intersertal texture. Calcite or chlorite-filled vesicles may be present.

All volcanic fragments are rounded to subrounded and are hence considered extrabasinal according to the criteria of Zuffa (1985, 1987).

4.2.3.8 Accessory Minerals

The heavy minerals listed in table 4.4 were identified mainly by using the Scanning Electron Microscope (SEM) Energy Dispersive Spectrometer (EDS) and backscatter capability. The disadvantage of this approach is that for a study of large

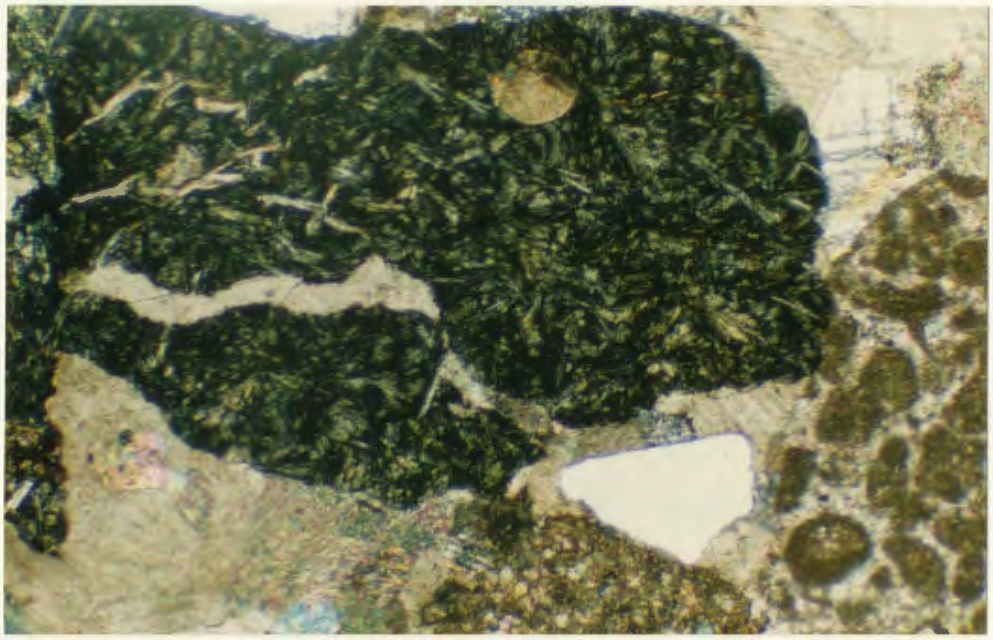


Plate 4.13: Lathwork volcanic fragment, intermediate to mafic. Note calcite-filled vesicle. Lower Head Formation. Crossed polars. X32.

numbers of grains, it is difficult to make a link between optical identification and identification in backscatter mode. The advantage is that since a standard thin section is all that is required, minerals such as apatite, which are destroyed by standard heavy mineral processing procedures, are preserved. Also opaque minerals may be identified using this method.

Some electron microprobe analyses from chromites of the Goose Tickle group are presented in appendix 3, section A3.7. Malpas and Strong (1975) have provided analyses for chromites from the Bay of Islands Ophiolite. These electron microprobe results are not directly comparable with those of Malpas and Strong (1975) since all iron in this study was analysed as FeO. Some qualitative comparisons, however, can be made. The chromite grains probed, which are angular, unzoned and unaltered, display a wide range of compositions. The high values of Cr_2O_3 and correspondingly low values for Al_2O_3 in many of the grains are typical of harzburgites which make up the major portion of the Bay of Islands Ophiolite. Some of the values are also within the range exhibited by dunites, which are more typical of the upper ultramafic levels of the Bay of Islands Ophiolite. None of the chromites show the elevated values for Al_2O_3 characteristic of the basal lherzolite layer of the Bay of Islands Ophiolite. Nor do they show the very high values of Cr_2O_3 characteristic of ultramafic rocks from the Gander River Ultramafic Belt in central Newfoundland (Malpas and Strong, 1975). The range of values for Cr_2O_3, MgO, and Al_2O_3, however, is compatible with those exhibited by ophiolites elsewhere (Press, 1986). No chromite analyses were conducted for the Lower Head Formation, however the grain characteristics are similar to those in the Goose Tickle

group, and qualitative compositional information obtained using the SEM EDS suggests a similar range in composition.

Monazite is common and may be subrounded or subhedral. Mica includes both biotite (some of which has been altered to chlorite), muscovite, and some green biotite. Biotite, which was qualitatively examined in SEM EDS, seems to be iron rich.

Rutile tends to be angular, and in places a titanium compound is observed to be associated with calcite, possibly indicating the alteration of sphene, which is found as euhedral grains in some samples.

The heavy mineral population as a whole tends to suggest a mixed source from recycled sediments (rounded zircon, monazite), mafic to intermediate rocks (biotite, amphibole), granitic and/or metamorphic rocks (euhedral zircon, sphene, monazite) and ultramafic rocks (chromite, pentlandite).

4.3 QUANTITATIVE PETROGRAPHY

The qualitative, interpretive approach taken above may be supplemented by a quantitative analysis of point-count data. However, the quantitative study described below must be considered of a reconnaissance nature only.

The most rigorous quantitative provenance studies are those such as that by Lundberg (1991). They involve point counting of a fairly large number of samples which have been previously screened and which display only minimum alteration (e.g. Lash, 1987, who only counted samples containing less than 10% matrix). The samples should be counted for as many parameters as possible using the Gazzi-Dickinson method,

and either a separate tally should be kept of coarse-grained rock fragments, or subsequent counts of rock fragments only should be made. In addition, vertical, through time, variations in modal percentages should be ideally be documented. To adequately document vertical variations, other parameters should be controlled. This means that for comparative purposes samples should always be collected from the same facies and from the same position in the bed.

Many studies (see for a summary e.g. Schwab (1986, 1991), and point counts summarised by Hiscott, 1984) provide quantitative data based on only a few samples per stratigraphic unit. Facies information is generally not provided, and vertical variations are not documented. Such data, while not treatable statistically, may yet be useful.

The quantitative aspect of this study falls between the two extremes described above. An ideal quantitative study was impossible to accomplish for several reasons:

1. The degree of alteration was so high in all samples from northern localities of the American Tickle formation that unsuitable samples had to be selected for point counting. In almost all cases the amount of matrix was high and use of Lash's (1987) matrix criterion would have resulted in the point counting of very few samples;
2. No documentation of vertical variations was attempted because it was considered that vertical facies variations would obscure compositional variations. Also the structural complexities in many sections where vertical changes might have been documented (e.g. Mainland) would have added additional uncertainty;
3. Among the three units it was difficult to sample from exactly comparable facies.

Although a limited number of samples were point counted, they were selected as

being representative of a much larger suite of (approximately 200) samples. The method employed in point counting grains was the Gazzi-Dickinson method as tested by Ingersoll et al. (1984) which was described in the introduction and which minimises the effect of grain size variation. The thin sections were first stained for both potassium feldspar and plagioclase using a slightly modified version of the method outlined in Quinn (1985). Part of each section was masked to allow for investigation of textural features which might have been obscured by the staining process. The thin sections were then point counted perpendicular to bedding using a Swift point counting stage to provide a regular grid spacing. The counts were entered into an IBM compatible personal computer directly using the program PCOUNT.BAS which causes the computer keyboard to act as a tally counter. Thirty counting parameters were employed, which are listed in table 4.5. The list was adapted from those of Ingersoll (1990) and Cavazza (1989). The spacing of the counting grid was 1 mm, in order to assure good coverage of the thin section. At least 350 points per thin section were counted, and for most sections, 400 points were counted (the number of points counted for each sample is listed in appendix 4, sections A4.1, A4.2, and A4.3). The grid spacing was carefully monitored to ensure that it was larger than the maximum grain size of grains within the section. Thus the counting error may be estimated using the chart of Van der Plas and Tobi (1965). Otherwise, no attempt was made to evaluate operator error.

Because of the choice of a 1mm grid spacing, samples selected for counting had a maximum grain size on the boundary between coarse and very coarse sand, with coarser samples being excluded from the point counting process. This means that the

Table 4.5: Point Counting Parameters

1. Monocrystalline quartz
2. Polycrystalline quartz with tectonite fabric
3. Polycrystalline quartz without tectonite fabric
4. Plagioclase feldspar
5. Potassium feldspar
6. Monocrystalline mica
7. Mono and polycrystalline phyllosilicate
8. Opaque mineral
9. Glauconite
10. Volcanic with glassy texture
11. Volcanic with aphanitic or equigranular texture
12. Volcanic with microlitic or lathwork texture
13. Slate/phyllite
14. Semischist
15. Quartz-feldspar-mica aggregate
16. Polycrystalline mica
17. Mudstone/shale
18. Laminated Shale
19. Micritic limestone
20. Sparitic limestone
21. Bioclast
22. Ooid
23. Small grains less than 0.03mm, and recrystallised clay matrix
24. Carbonate cement
25. Quartz cement
26. Unidentified
27. Non-Opaque heavy mineral
28. Chert
29. Siltstone
30. Altered potassium feldspar/plagioclase feldspar

very coarse LH1 facies of the Lower Head Formation was excluded from the counts, but it was felt that this should allow for better comparison between the units. The average grain size of counted samples was therefore approximately medium- to coarse-grained. Zuffa (1987) suggested that only medium grained sandstones be counted where possible, however, since many of the samples collected for this study were coarse grained, exclusion of coarse grained samples would have eliminated a large proportion of the sample set. In addition, fine-grained samples tended to contain a high proportion of pseudomatrix, rendering the likely error higher. However, the grain size of samples counted was still fairly restricted, and use of the Gazzi-Dickinson point count method minimises variations in modal percentages as a result of grain size variations (Ingersoll et al. 1984; Zuffa, 1985). Some of the samples counted were considerably altered, particularly from the American Tickle formation whose generally sand-poor nature resulted in fewer available samples, but it was felt that, having defined this as a reconnaissance study rather than a rigorous provenance study, the information derived from altered samples was nevertheless useful.

Dickinson et al. (1983) suggested that sandstones with an amount of matrix plus cement greater than 25% should not be included on tectonic discrimination diagrams. In this case samples with both greater than and less than 25% matrix plus cement are plotted on the discrimination diagrams, but are distinguished by different symbols.

The data produced by the point counting process were imported into a spreadsheet (Lotus 1,2,3 version 2.2) and recalculated to give the parameters outlined in appendix 4, sections A4.1, A4.2, and A4.3.

Some discussion is required regarding the point counting parameters, in particular where they differ from those of Cavazza (1989). Only unaltered or very slightly altered grains were counted in category 5 (potassium feldspar). A separate category (30, altered potassium feldspar/plagioclase feldspar) was included because in many cases, determination of whether the original grain was potassium feldspar or plagioclase was not simple (see discussions in sections on feldspars).

Category 7 (monocrystalline and polycrystalline phyllosilicate) included detrital chlorite and grains which were initially identified as serpentine. Discussions above have shown that although both volcanic and plutonic sources may provide detrital chlorite, the vast majority of these grains were probably derived from an ultramafic source. While many of the chlorite grains were ultimately of ultramafic origin on textural grounds and therefore are plutonic rock fragments, it was felt to be more accurate to simply classify these fragments on the basis of the identified minerals rather than on an interpretive basis. As well, the Gazzi-Dickinson method does not allow for the counting of plutonic rock fragments. Category 12 included volcanic rocks with both microlithic and lathwork texture. Several authors have suggested (Dickinson, 1970; Boggs, 1992) that lathwork grains with intersertal texture indicate a basaltic origin, whereas microlithic grains suggest an intermediate origin. These two categories were not distinguished in point counting. However, it should be noted that a ratio of this category to total volcanic fragments will give an indication of the proportion of mafic/intermediate fragments in the sample, as the other two categories contain only felsic volcanic fragments.

Category 18 (laminated shale) was included to distinguish distinctive organic rich

laminated shale chips which were felt to be important provenance indicators. This category was considered distinct from unlaminated shales and mudstones. Category 19 includes both micritic and sparry limestone fragments, although for all units, sparry limestone fragments are uncommon. Category 20 (detrital sparry calcite) was reserved for grains which appear to represent altered grains of a pre-existing feldspar or mafic mineral. If the original mineral could be identified, however, the fragment was counted as the original mineral. The ooid category (22) includes both calcium carbonate ooids and rare chamositic ooids.

4.3.1 Petrographic Data

Raw data and recalculated petrographic parameters for the American Tickle, Mainland and Lower Head formations are given in appendix 4, sections A4.1, A4.2, and A4.3. The list of parameters which were included in the raw count is that given in table 4.5. In appendix 4, information is given regarding the number of grains counted, the percentage of matrix+cement, and the percentage of matrix+cement+calcite grains. The latter parameter is useful because sparry calcite grains are interpreted as altered framework grains, and the parameter hence gives a more accurate impression of the level of alteration within the sample. Calculations of the parameters plotted on triangular diagrams in figures 4.6 through 4.11 are also provided. Two additional parameters are listed in appendix 4, they are the ratio P/F, and the ratio Lph/Lt. P/F is the ratio of plagioclase to total feldspar. Although this ratio has been used in the determination of provenance, it is unclear how meaningful it may be in this case, given the alteration

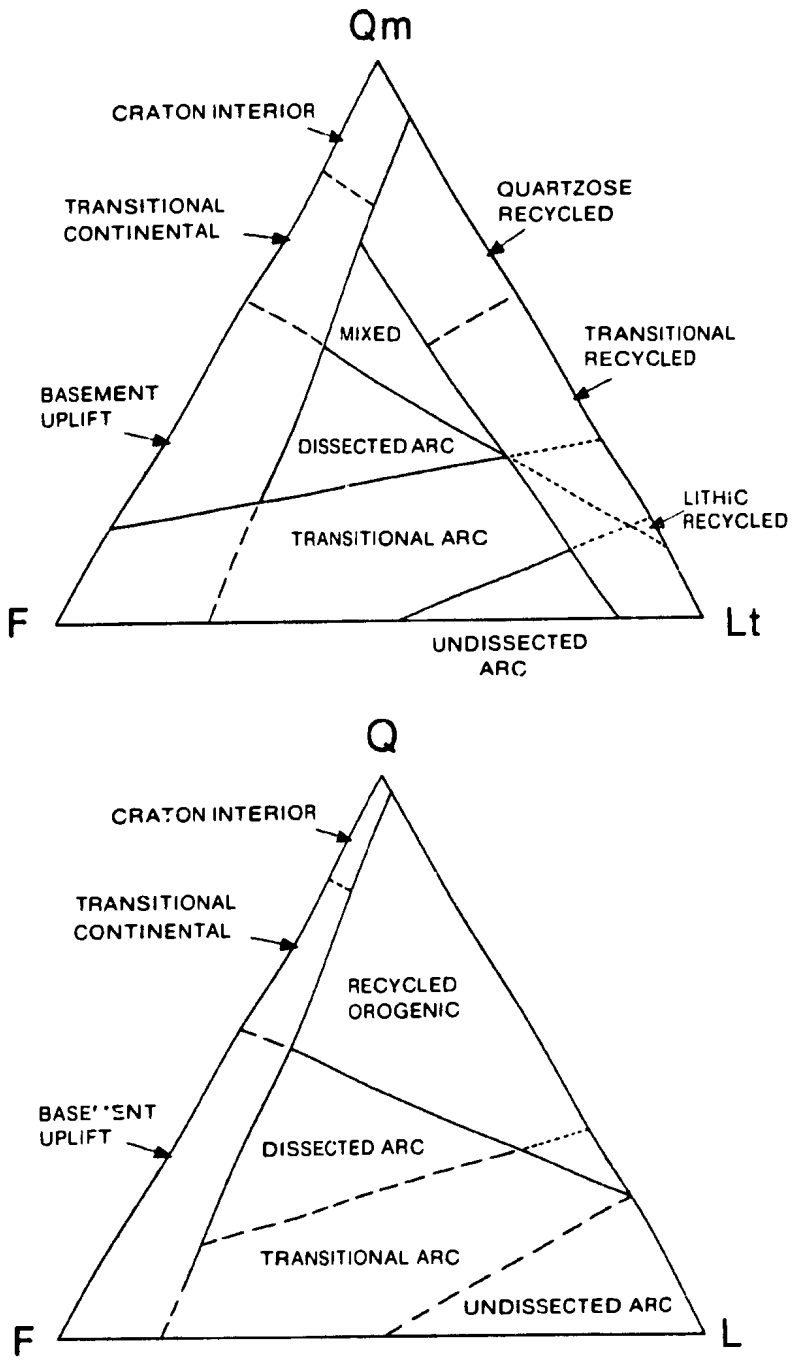


Figure 4.5: Plate tectonic settings for various sandstone compositions, after Dickinson et al. (1983).

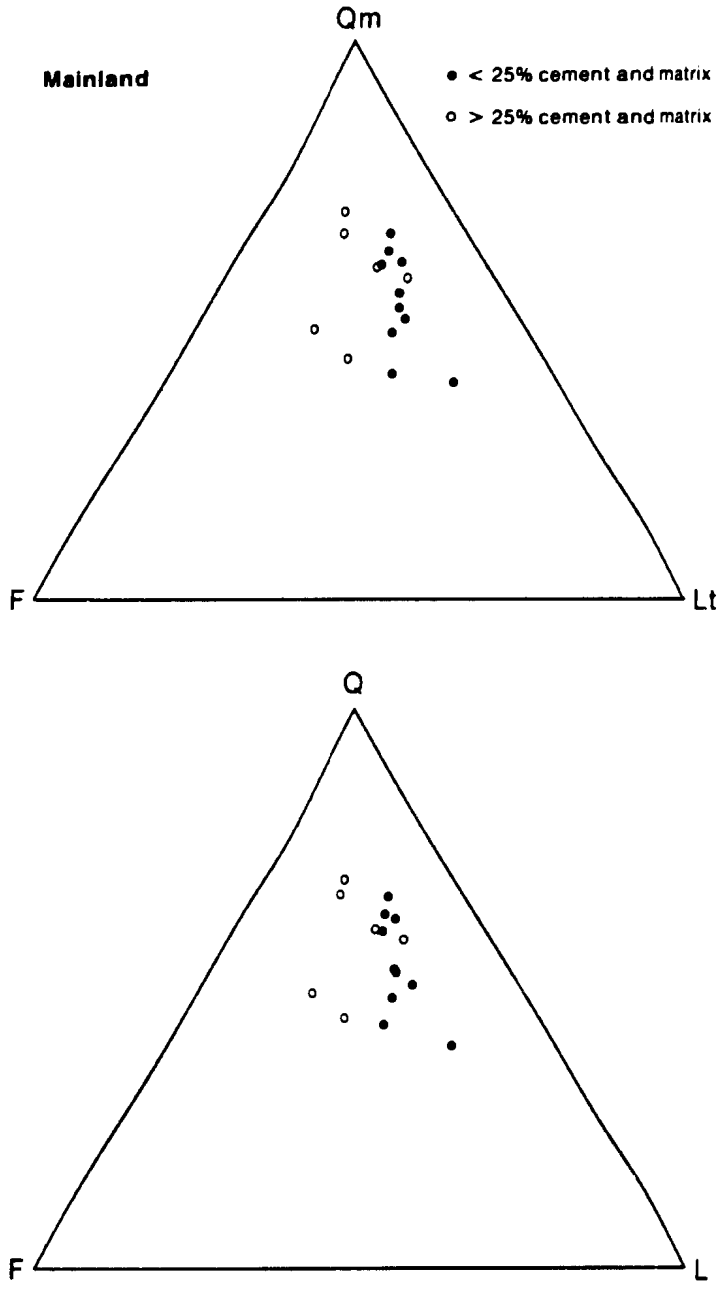


Figure 4.6: QFL and QmFLt plots for the Mainland formation.

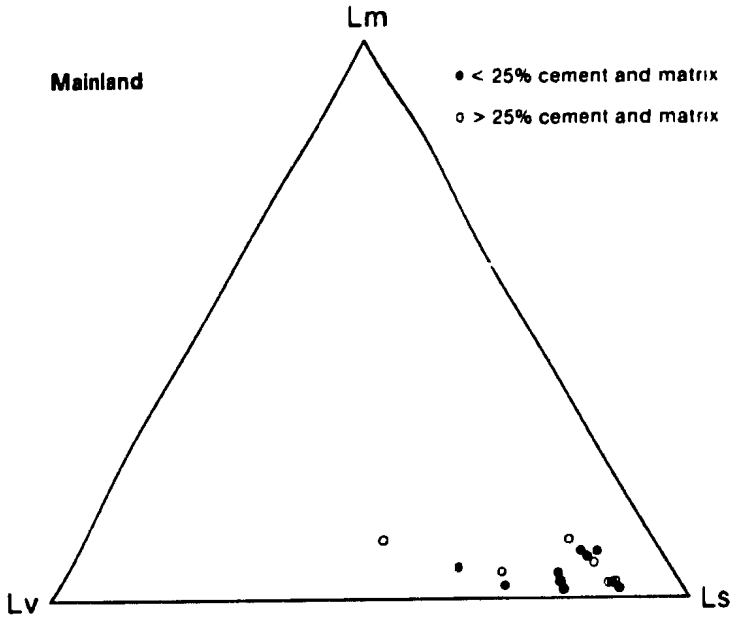


Figure 4.7: LvLmLs plot for the Mainland formation.

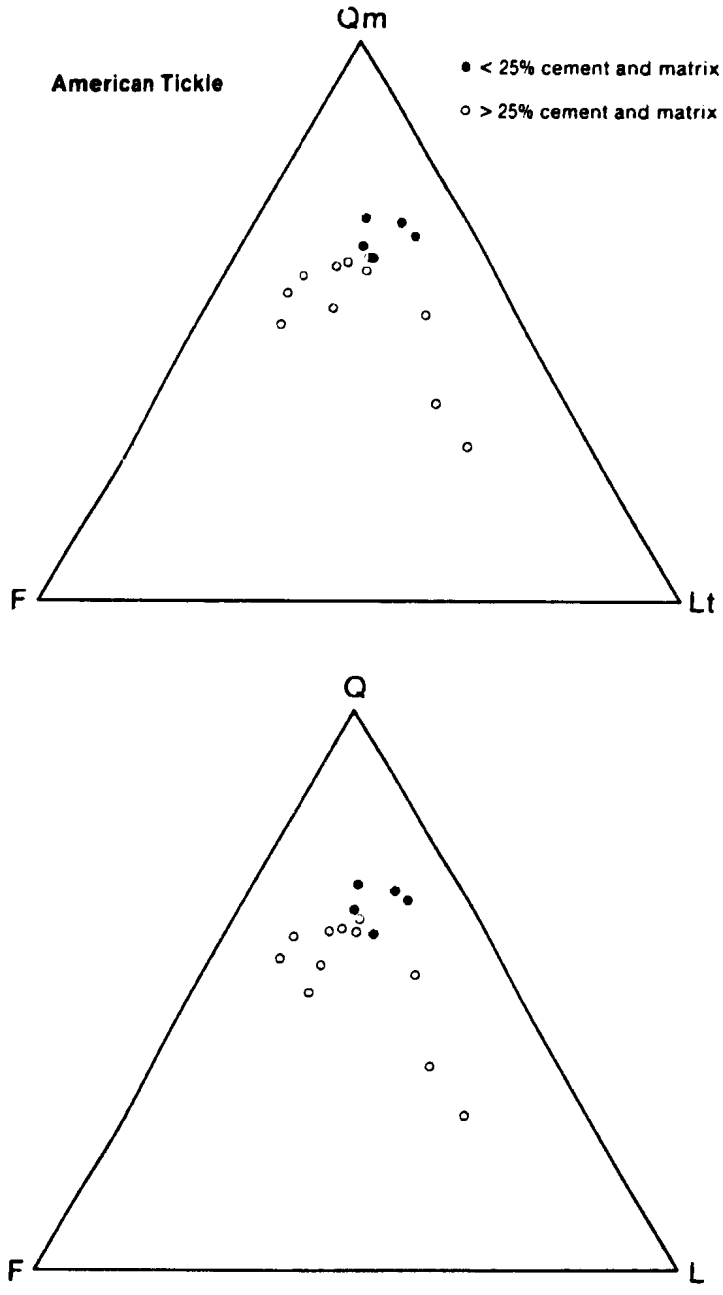


Figure 4.8: QFL and QmFLt plots for the American Tickle formation.

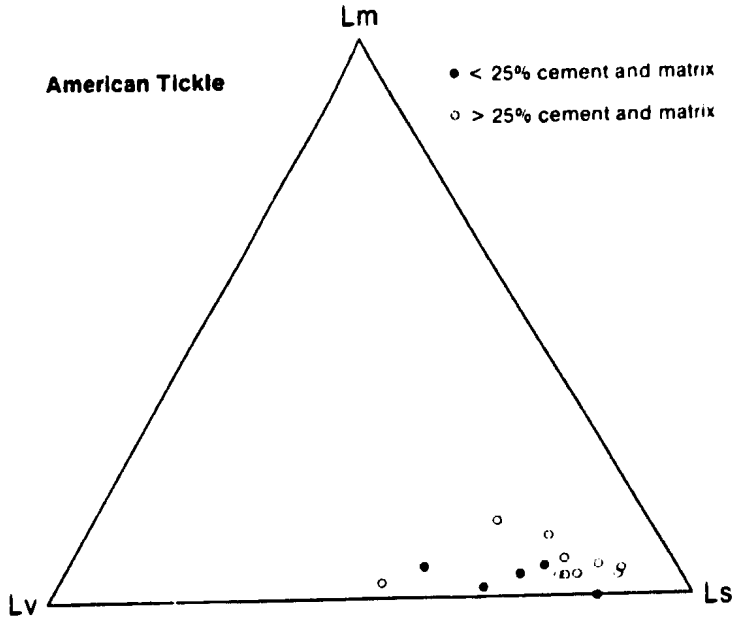


Figure 4.9: LvLmLs plot for the American Tickle formation.

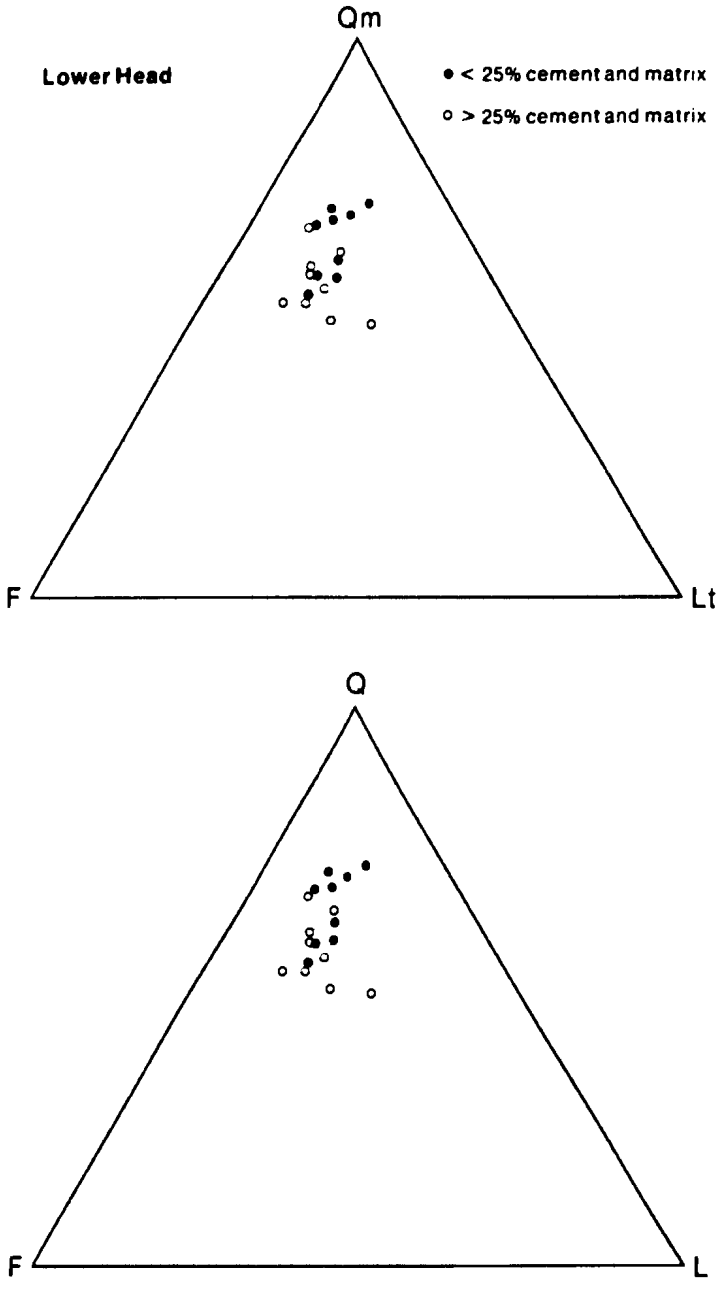


Figure 4.10: QFL and QmFLt plot for the Lower Head Formation.

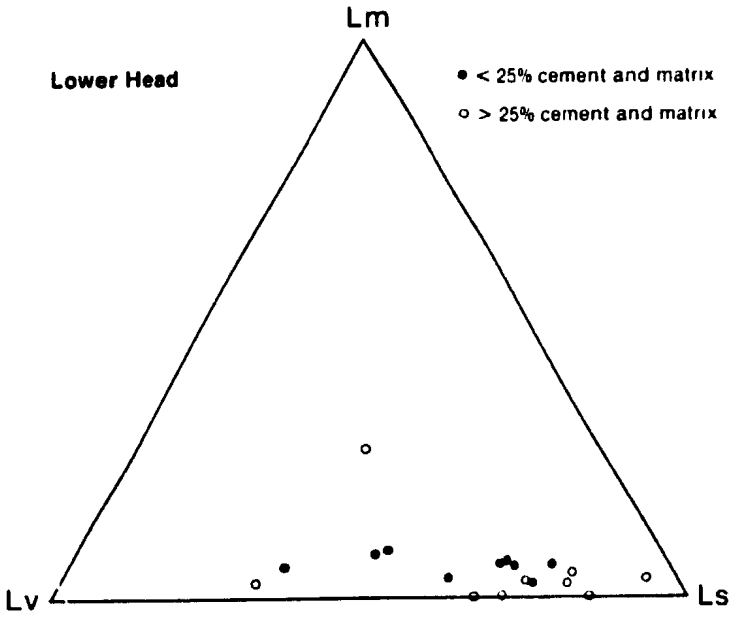


Figure 4.11: LvLmLs plot for the Lower Head Formation.

characteristics of potassium feldspar. For the same reason, no plots which depend on the relative proportions of the two types of feldspar have been presented. The ratio Lph/Lt is introduced here and is the ratio of the number of phyllosilicate grains over all other total non-carbonate lithic fragments (the traditional Lt). Since the bulk of Lph grains are interpreted as being of ultramafic origin (chloritised serpentine), this gives an indication of the relative importance of ultramafic fragments within a sample.

Sixteen samples from the American Tickle formation were counted with average values of Q - 56.79 (s.d. 11.14), F - 20.33 (s.d. 7.22), and L - 22.88 (s.d. 11.31). Sixteen samples from the Mainland formation were counted, with mean values of Q - 55.83 (s.d. 9.02), F - 17.96 (s.d. 6.01), and L - 26.20 (s.d. 7.69). Eighteen samples from the Lower Head Formation were counted showing average values of Q - 60.12 (s.d. 7.32), F - 24.93 (s.d. 5.09), L - 14.95 (s.d. 4.45). QFL plots and QmFLt plots for each formation are shown in figures 4.6, 4.8, and 4.10. To distinguish trends, and because of the statistical invalidity of plotting average values, only individual values are shown, following the suggestions of Philip and Watson (1988).

For all three formations, there is little difference between a plot of QFL and QmFLt (figures 4.6, 4.8, 4.10), indicating the minor importance of polycrystalline quartz as a rock fragment. The American Tickle formation, which is generally altered (see discussion above) shows considerable scatter of points, particularly in the samples with high matrix+cement. The most lithic rich samples both come from the Table Cove locality, suggesting a local input of lithic fragments, in this case shale chips. The Mainland formation shows more scatter than might be expected from its restricted areal

extent. Samples from near the top of the formation tend to be more quartz rich, suggesting that the apparent trend shown on the plot might be a result of a variation in provenance through time (but see discussion above). However, it could also be a function of the greater degree of reworking of sands at this level within the Mainland formation. A simple variation in depositional processes without change in composition of sediment supply can cause a change in modal percentages of grains present (see, e.g. Zuffa, 1985). Although the following is not a statistically rigorous statement (see Lash, 1987; Ingersoll, 1990), it appears that because of overlap of standard deviations, the Mainland formation cannot be considered petrographically distinct from the American Tickle formation.

The Lower Head Formation shows a fairly good cluster of both matrix and non-matrix rich samples from widely spaced localities, which might be considered surprising in light of the complex depositional setting implied for the Lower Head Formation in chapter 3. In addition, the Lower Head Formation can be considered petrographically distinct (within one standard deviation) from the other two units as it contains less lithic fragments.

All three units plot in the recycled orogen fields of Dickinson et al. (1983) (figure 4.5), or in or close to the 'mixed' fields of Dickinson (1988). This is to be expected from the qualitative description of the rock fragments present. All three units are dominated by sedimentary rock fragments (see figures 4.7, 4.9, 4.11), but the Lower Head Formation shows a wider range of volcanic rock fragments vs. sedimentary rock fragments. Plots of LvLmLs indicate varying proportions of sedimentary vs. volcanic

rock fragments, with only minor input from a metamorphic source. As carbonate fragments were not included in the plot, it is clear that shale fragments represent the bulk of the sedimentary rock fragments. The importance of Lph varies from sample to sample, but is clearly very abundant in some samples. A review of the three types of volcanic rock fragments shows that for most samples, siliceous volcanic rock fragments dominate. The abundance of siliceous rock fragments in Ordovician sandstones in western Newfoundland has previously been unrecognised (see discussion in chapter 1).

4.4 SUMMARY AND CONCLUSIONS

Utilising the information in Chapter 3 and this chapter, the following sources have been identified for the Lower Head Formation and the Goose Tickle Group from consideration of the rock fragments and framework grains present.

1. Intermediate/mafic volcanic rocks;
2. Mafic plutonic rocks;
3. Felsic volcanic rocks;
4. Felsic plutonic rocks;
5. Intraformational/intrabasinal sediments of local origin;
6. Lithified sedimentary rocks;
7. Shallow water carbonates;
8. Black and green shale.

Clearly all of these can be considered extrabasinal except category 5. In addition, utilising information from chapter 3, it is possible to subdivide the extrabasinal category

into two types:

a) sources which were clearly completely extrabasinal (categories 1,2,3, and 4);

b) 'marginal extrabasinal' which are interpreted to represent materials identifiably eroded from the eastern margin of the basin. These would include mainly sedimentary rocks i.e. 8 which is interpreted to represent easterly equivalents of the Goose Tickle group and underlying units, and parts of 6 which would include the Cow Head clasts in the Lower Head conglomerates. Category 6 also seems to include a pervasive but unrecognisable shallow water source with both uncemented oolites and silica cemented quartzo-feldspathic sandstones.

It is category 8 which is the most abundant rock fragment percentage, suggesting a dominant signature from the basin margin. Volcanic fragments are dominated by siliceous varieties and plutonic fragments are primarily chloritised serpentine.

With regard to framework grains other than rock fragments, one of the most obvious questions is the origin of the quartz population, as it is dominated by monocrystalline quartz grains. Quartz is one of the most problematic parameters from which to determine provenance (Basu, 1985), which is unfortunate in view of its abundance in most sandstones. Few of the monocrystalline quartz grains in the Goose Tickle group and Lower Head Formation are unambiguously of volcanic origin, therefore four main possible sources remain:

1. Plutonic felsic rocks;

2. Metamorphic rocks;

3. Recycled sedimentary rocks;

4. a combination of any or all of the three listed above;

Consideration of the rock fragments shows that clearly 1,2, and 3 have provided detritus to these sandstones. If relative proportions of rock fragments only are considered, the contribution by 2 and 3 appears minimal in comparison to the contributions by 1; however, the extremely well rounded nature of some of the quartz grains suggests that some at least have been recycled, although abraded overgrowths are few, and that a sedimentary source cannot be ruled out for the bulk of the monocrystalline quartz grains.

Feldspars are enigmatic. Potassium feldspars seem to indicate a plutonic or metamorphic source. Plagioclase feldspars may have been supplied directly from a plutonic or metamorphic source, or they may have been supplied through recycling of a sedimentary or low grade metamorphic rock in which a substantial proportion of feldspars had been albitised. The 'altered' grains are generally not euhedral and the shape of the cores relative to the exteriors suggests that they may have been incorporated in sediments which were buried and then uplifted before alteration of albite to k-spar was incomplete.

Although some plagioclase feldspars may have been supplied by a volcanic source, it is thought that the chemistry of the bulk of the feldspars, the paucity of preserved individual small plagioclase laths, and the lack of zoned sand-sized crystals implies that the supply of feldspars directly from a volcanic source are few. This would imply a plutonic or metamorphic or recycled sedimentary source for the majority of the plagioclase feldspars.

Source types as inferred from accessory minerals are in general agreement with

those inferred from framework grains.

The dominance of extrabasinal rock fragments clearly places sandstones of the Goose Tickle group and the Lower Head Formation as type A arenites of Zuffa (1991) which is consistent with the depositional setting inferred for these units in chapter 3. The 'mixed' provenance implied by the data on modal percentages is also consistent with this depositional setting.

Despite the large area over which samples were collected, petrographically both the Goose Tickle group and Lower Head Formation are fairly homogeneous. This combined with the variable rounding of grains suggests mixing of the source materials prior to supply of sediment to the main foreland basin and trench slope basin(s). It seems therefore, that petrographic studies at this level of detail will not allow one to distinguish whether the Lower Head Formation was deposited in one or more than one basin.

Clearly, the possibility of a substantial sedimentary or metasedimentary source for these rocks requires further investigation, as does the prominent felsic and ultramafic signature in the igneous fragments. In addition, a link should be attempted between the types of rock fragments identified here, and the 'hinterland' area to the foreland basin. These tasks will be undertaken in chapter 6.

CHAPTER 5

GEOCHEMISTRY

5.1 INTRODUCTION

The discussion in this chapter includes only the bulk geochemical characteristics of the Lower Head Formation and the Goose Tickle group. Geochemistry of specific minerals has already been discussed in chapter 4, and bulk geochemistry of Cambrian sandstones will be discussed in chapter 6.

5.1.1 Terminology

A major element is one which is normally abundant in rocks, and belongs to a standard list of the elements which predominate in rocks, viz. Si, Al, Ti, Fe, Mn, Mg, Na, K, and Ca. A trace element is one which is commonly present in small quantities in rocks (less than 0.1%). Rare Earth Elements (REES) are a group of trace elements which fall into the transition area of the periodic table and whose similar chemical characteristics cause them to behave in a similar fashion chemically. REES will be treated separately in this chapter.

5.1.2 Analytical Methods and Problems

Nineteen representative samples of both Cambrian and Ordovician sandstone units were analysed in the laboratories at Memorial University of Newfoundland, using Atomic

Absorption Analysis (AAA) for major elements, X-Ray Fluorescence (XRF) of pressed pellets for some trace elements, and Inductively Coupled Plasma Mass Spectrometry (ICPMS) for rare earth elements. Some of the original trace element data, particularly that for Cr and Ni (which had anomalously low and in some cases negative values) were considered suspect and the samples were reanalysed by XRF of pressed pellets at Activation Laboratories, Ancaster, Ontario, with additional analyses of some trace elements not included in the Memorial package. Activation Laboratories data proved to be reproducible whereas Cr and Ni data from Memorial were not, and Activation Laboratories data were used for all available elements.

A further 88 samples were analysed by a combination of Neutron Activation Analysis (NAA), and Inductively Coupled Plasma analysis of fused pellets at Activation Laboratories, Ancaster, Ontario. Inspection of the NAA data from Activation Laboratories showed that some samples from Cambrian units contained much higher values of Cr than would have been expected. Further investigation showed that the crushing method used by Activation Laboratories involved use of a hard steel mill, which can contaminate samples with 20 - 200 ppm chromium. Chromium abundances for the Lower Head Formation and Goose Tickle group had not initially been considered to be anomalous as they were within the range of values expected from previously published information (Hiscott, 1984) but contamination was found to range from approximately zero for soft friable samples, to 150 ppm for hard samples from the Cambrian units which had originally been identified as anomalous.

Activation Laboratories offered to recrush and reanalyse the samples for Cr, but

a number of small samples had been completely crushed for the first analysis and could not be reanalysed. The original Cr data for these samples were retained and treated in the following way. Each formation was considered separately, and samples from the same formation were assumed to have similar hardness. Thus a mean value of the contamination for each formation was calculated (see appendix 5). This amount was then subtracted from the original Cr values for each sample. For all other samples, the individual Cr values from the reanalysis were used. Clearly, this is not an ideal or rigorous approach, but it may be justified for the following reasons. Firstly, absolute values of Cr are high for the Goose Tickle group and Lower Head Formation, and since the analytical precision at these concentrations is on the order of 10%, the contamination levels can be considered small relative to the uncertainty already incorporated in the data. Secondly, the discussion of chromium concentrations in this chapter does not emphasise individual absolute values, but rather the variation among values, which will not be substantially affected by this treatment. However, if the reader does not accept these justifications, then inferences made below regarding the behaviour of Cr in factor analysis should be disregarded.

The geochemical data obtained through the analyses discussed above, as well as some of the recalculated parameters referred to in this chapter, are displayed in appendix 5. sections A5.1 through A5.6. Appendix 5 also contains a brief description of the elements and samples analysed by each method and the precision of these methods. Means and standard deviations for the data, correlation matrices and other statistical data are presented in appendix 6. A key to locality abbreviations (for sample names) is given

in appendix 1. For comparative purposes the data have been recalculated to 100% volatile free. Trace element data have not been recalculated, however, because this does not seem to have been the practice among most authors who have studied trace elements in sandstones (e.g. Hiscott, 1984; Van de Kamp and Leake, 1985).

5.1.3 Geochemistry of Sandstones - Discussion

There has been some disagreement as to whether shales or sandstones can be considered more accurate indicators of provenance (e.g. Blatt, 1985; Van de Kamp and Leake, 1985). Blatt (1985) has argued that mudrocks may in some instances be superior to sandstones because of their greater impermeability and hence their greater resistance to diagenetic effects. However, shales, with their high clay mineral content, may contain a significant amount of adsorbed material which reflects the chemistry of the seawater. Seawater chemistry is a function of a number of factors and may not be entirely reflective of provenance. Several authors have noted that the most complete characterisation of the chemistry of a sedimentary unit should be based on analyses of both sandstones and any interbedded shales (Van de Kamp and Leake, 1985; Roser and Korsch, 1986, 1988). Van de Kamp and Leake (1985) concluded, on the basis of such an integrated study, that chemically, sandstones are better indicators of provenance than shales.

Interpretation of chemical analyses of sandstones should be made with caution. Factors which affect sandstone chemistry are similar to those which affect framework grain proportions and include provenance, weathering, mode of deposition and

diagenesis.

As might be expected from petrographic considerations (e.g. Ingersoll et al., 1984), among sandstones of similar provenance, grain size variations have a significant effect on chemistry (Roser and Korsch, 1985, 1986, 1988). Two approaches may be utilised to minimise this problem. The first is to analyse only samples from a restricted grain size range (e.g. Bhatia, 1983, 1985), but this may result in loss of information for certain suites of samples if coarse grained samples are excluded from a study. The second approach involves the analysis of the full range of grain sizes available. In using this approach, several authors (Van de Kamp and Leake, 1985; Roser and Korsch, 1985, 1986) have noted that diagrams used to illustrate geochemical variations should show plots of individual analyses rather than means of sample populations. The diagrams then distinguish trends among sample populations.

In this study a wide range of grain sizes in sandstones was analysed, from fine sand to very coarse sand, but no shales were included. Some geochemical information on shales of the Goose Tickle group and Lower Head Formation is available through the work of Garver and students (pers. comm. 1991). Botsford (1988) has also analysed some shales from the base of the Lower Head Formation. Information from these studies will be incorporated into the general synthesis of chemical information from the sandstones of these units.

The potential effects of diagenesis have rarely been directly addressed, but Maynard et al. (1982) investigated the relationship between the chemistry of sandstones and that of associated shales, and concluded in particular that the high Na_2O content of

ancient greywackes is similar to that of modern greywackes, thus suggesting that the sodium has not been introduced through diagenesis. Roser and Korsch (1986) have admitted that Na and K may become mobile under conditions of diagenesis, although they have suggested that the overall bulk chemistry of the rock may not change even under conditions of low grade metamorphism.

Normark (1985) has noted the potential effects of facies variations on provenance information. For example reworked and unreworked sands from the same source may have different chemical compositions, as clay minerals may have been removed during the reworking process. This may result in a depletion in the reworked sand of such elements as Cr, Ni, Ti, Rb, Y, and Zn, which tend to reside in clay minerals (Van de Kamp and Leake 1985). Basu et al. (1990) have noted trace element enrichments indicative of heavy mineral sorting in fluvial sands. Similarly in turbidites, heavy mineral enrichments may occur in the B division of the Bouma sequence, so that even the part of the bed from which the sample is collected may affect the chemistry. Despite this, however, facies information has rarely been incorporated in general investigations of sandstone geochemistry. Van de Kamp and Leake (1985) referred to their samples simply as sandstones but did provide petrographic data and a general statement of environment of deposition. Roser and Korsch described their samples using general terms such as greywacke, sandstone, and arkose. Maynard et al. (1982) as well as Taylor and McLennan (1985) employed the rather vague term greywacke. However, in general, chemical characteristics of these 'greywackes' of the literature should be comparable to sandstones in this study, since greywacke (a matrix rich sandstone with

abundant feldspar and lithic fragments) is the most common rock type found in turbidites. For this study, grain size and sedimentary structures of each sample were recorded and are included in the data tables in appendix 5.

5.2 MAJOR AND TRACE ELEMENT GEOCHEMISTRY

5.2.1 Discussion - Major Elements

Major element geochemistry of sandstones has been used in several ways to enhance or support provenance studies. Several studies have employed variation diagrams based on K_2O/Na_2O ratios vs. percentage of silica to separate sandstones of different provenance (e.g. Maynard et al. 1982; Roser and Korsch, 1986). Maynard et al. (1982) analysed a number of modern deep sea sands, and suggested that while passive margin sandstones and those from forearc basins are chemically distinctive, those from other arc-related basins may be indistinguishable from each other.

Bhatia (1983) suggested that the parameters which most successfully discriminate among sandstones of different provenance are $(Fe_2O_3+MgO)\%$, $TiO_2\%$, Al_2O_3/SiO_2, K_2O/Na_2O and $Al_2O_3/(CaO+Na_2O)$. These parameters were used by Bhatia (1983) to distinguish four provenance types - oceanic island arc, continental island arc, active continental margin, and passive continental margin. Bhatia (1983) stated that there is a progressive decrease in $(Fe_2O_3+MgO)\%$, $TiO_2\%$, and Al_2O_3/SiO_2, and an increase in K_2O/Na_2O and $Al_2O_3/(CaO+Na_2O)$ in sandstones from oceanic island arcs to continental island arcs, to active continental margins, to passive margins. He estimated the range of values for these parameters for each of the different provenance types and these are

shown in table 5.1. Utilising these parameters, Bhatia (1983) showed variation diagrams, and also employed the statistical method of discriminant analysis to construct discrimination diagrams. His diagrams are limited in that they only apply to sandstones in the fine to medium grain size range. The database on which the diagrams were constructed was restricted to five Paleozoic turbidite sequences in eastern Australia, and did not contain any modern sands from known tectonic settings.

Roser and Korsch (1986) produced a variation diagram based on analyses from suites of sandstones and their interbedded shales, and concluded that three main groups, arc, active margin, and passive margin may be distinguished on the basis of a plot of K_2O/Na_2O vs. $SiO_2\%$. Roser and Korsch (1988) subsequently expanded their work to produce variation diagrams using similar parameters to those outlined by Bhatia (1983). They found that these plots were moderately, but not completely, successful in discriminating sandstones from different provenances, and thus they subjected a large number of sandstone/mudstone samples of known provenance to discriminant analysis. The method of discriminant analysis, they suggested, is much more successful in discriminating sandstones of different provenance, and reduces but does not completely eliminate the grain size effect.

Roser and Korsch (1988) tested the viability of their discriminant functions on chemical analyses of numerous sandstones of known provenance from the literature, and also on igneous rocks which are potential sources. Rather than trying to distinguish sandstones from different plate tectonic settings, Roser and Korsch (1988) discriminated on the basis of source lithology, including: P1 (mafic - first cycle and lesser andesitic

Table 5.1

Estimates of chemical characteristics of sandstones of various provenances (from Bhatia, 1983)

	OA	CA	ACM
$(Fe_2O_3+MgO)\%$	8-14%	5-8%	2-5%
$TiO_2\%$	0.8-1.4%	0.5-0.7%	0.25-0.45%
Al_2O_3/SiO_2	0.24-0.33	0.15-0.22	-
K_2O/Na_2O	0.2-0.4	0.4-0.8	1
$Al_2O_3/(CaO+Na_2O)$	-	-	-

Note: OA=Oceanic arc. CA=continental arc. ACM=active margin. No values given for passive margin sandstones. They are 'generally enriched in SiO_2 and depleted in Na_2O, CaO, and TiO_2, suggesting their highly recycled and matured nature'.

detritus); P2 (intermediate - dominantly andesitic detritus); P3 (felsic - acid plutonic and volcanic detritus); P4 (recycled - mature polycyclic quartzose detritus). Roser and Korsch (1988) also noted the importance of biogenic carbonate in altering the results, and produced a second set of discriminant functions which were designed for samples with significant quantities of biogenic carbonate. This second set of functions was considered to be less efficient at discrimination among sandstones of different provenance, but was felt to be 'adequate'.

5.2.2 Discussion - Relationships Between Major and Trace Elements

Few studies of sandstone chemistry have investigated the relationships between major and trace elements. One exception is a study by Van de Kamp and Leake (1985) who plotted various major and trace element parameters on scatter plots to examine correlations. A thorough investigation of the relationships of major element parameters to each other and to trace element concentrations, clearly characterises the chemistry more completely than if major or trace elements are considered separately. Another advantage of the general approach employed by Van de Kamp and Leake (1985) is that the major element parameters employed were Niggli numbers, which are defined in table 5.2. Since Niggli numbers are ratios, their use to some extent reduces the constant sum or closure effect which occurs in any set of data expressed in percentages (Van de Kamp and Leake, 1985; Chayes, 1960). This constant sum effect is particularly marked in bulk rock chemistry, since the dominant oxide in most rock types is silica, and most other elements will vary antipathetically with silica (Roser and Korsch, 1986). Some important

Table 5.2

Definitions of Niggli Numbers

From Tomkeieff (1983): Niggli values - The weight percentages of the chemical analysis of an igneous rock are divided by the molecular weight of the corresponding oxide, producing the molecular numbers. These are then regrouped, added and recalculated to 100 to produce the Niggli values si, al, fm, alk, mg and k.

si =
mol cont. Si_2O_3/mol(Al_2O_3+CaO+FeO+Fe_2O_3+MnO+MgO+Na_2O+K_2O)

al = Al_2O_3/ "

fm = (FeO+Fe_2O_3+MnO+MgO)/ "

alk= (Na_2O+K_2O)/ "

mg= MgO/mol(MgO+FeO+2Fe_2O_3+MnO)

k= K_2O/mol(K_2O+Na_2O)

Note: after Van de Kamp and Leake (1985)

Niggli parameters (notably al-alk and mg) are independent of the variation in silica content. Ratios are also useful for comparative purposes as data from other sources need not necessarily be recalculated.

A particularly important Niggli parameter is al-alk which measures the aluminium present in the material which is in excess of the Al combined with alkalies in feldspar (Van de Kamp et al. 1976). Therefore plotting of concentrations of various trace elements against al-alk may enable one to determine which elements are present in sheet silicates and which are present in feldspar or other minerals.

The data base for the study of Van de Kamp and Leake (1985) was restricted to the western U.S.A., but did contain numerous modern sands from known tectonic settings as well as Mesozoic and Cenozoic samples. Van de Kamp and Leake (1985) concluded that combined major and trace element geochemistry of sandstones can be used in evaluating sandstone provenance, but that the data should be interpreted carefully. They re-emphasised the need to be aware of the effect of grain size on geochemistry, and they found general but not specific agreement with the conclusions of Bhatia (1983) when they plotted suites of rocks of known tectonic setting on his discriminant diagrams.

5.2.3 Discussion - Trace Elements

Trace element geochemistry has been used by several authors to aid in the determination of provenance. Van de Kamp and Leake (1985) included trace elements in their comprehensive study which was discussed in the previous section, and were able to use their relationships to major element parameters with some success to ascertain in

which minerals trace elements were residing.

A notable study relevant to this thesis was that carried out by Hiscott (1984) who studied trace elements from foreland basin and related Ordovician sandstones from the entire length of the Appalachian Orogen. He was able to distinguish a significant difference in the concentrations of Cr and Ni in sandstones from the northern Appalachians vs. those the southern Appalachians. Garver (1990, pers. comm.) and students utilised a similar approach to that of Hiscott (1984) on Appalachian shales and their results were in general agreement with his. Both of these authors examined variations among trace elements by subjecting their data to factor analysis.

Factor analysis is a statistical method which attempts to reduce a large set of data with many variables into a lesser number of underlying variables, each of which may then be interpreted in terms of its geological significance (Davis, 1986). Two different but related types of analysis, Q and R mode, may be employed. Q mode factor analysis involves the analysis of relationships between samples on the basis of all the variables, R mode analysis involves comparison of relationships between variables on the basis of all samples. Q mode factor analysis has been applied to modal compositions of sandstones, in particular heavy mineral compositions (Imbrie and Van Andel, 1964; Thornburg and Kulm, 1987). R mode factor analysis has been applied to trace element geochemistry (Hiscott, 1984; Weber and Davis, 1990; Garver, pers. comm. 1991).

Weber and Davis (1990) applied a combination of R and Q mode analysis to trace element geochemistry in stream sediments. Hiscott (1984) carried out R mode factor analysis of trace element data from Ordovician Appalachian sandstones and was able to

isolate and interpret two factors which explained a large percentage of the variance within his trace element data. It should be noted that not all geochemical data may be suitable for factor analysis, and appropriate selection of variables is necessary (Davis, 1986). It has been suggested, as a rule of thumb (SAS/STAT users guide, 1988), that there should be at least three variables corresponding to each factor, and that the number of samples should exceed the number of variables by at least fifty (Lawley and Maxwell, 1971), although this is debatable (Geweke and Singleton, 1980). Weber and Davis (1990) analysed 35,000 samples, whereas Hiscott (1984) analysed 177 samples for 7 variables, and Garver (1990 pers. comm.) analysed 60 samples for 7 variables.

Variable selection for factor analysis may involve judgement as to which trace element parameters are important for provenance. Several authors (Bjorlykke, 1974; Van de Kamp and Leake, 1985; Hiscott, 1984; Garver, pers. comm. 1990) have paid particular attention to the behaviour of Cr and Ni as being relatively immobile elements indicative, when present in abundance, of an ultramafic source. Other key trace elements include Zr, Y, Ti, V, Co, and Cu. Most of the following information regarding the behaviour of these elements within a sedimentary rock is to be found in Wedehpol (1978).

Chromium in sandstones is considered to be predominantly supplied by the mineral chromite (Hiscott, 1984), although clearly the discussion of chlorite analyses in chapter 4 indicates that significant concentrations of chromium may occur in these minerals, and adsorption of the Cr ion on clay minerals is also possible. Nickel may be supplied in the mineral pentlandite, and also substitutes in mafic minerals such as olivine

and pyroxene. Nickel ions are soluble and are commonly carried in solution until final adsorption onto clay minerals within a sediment. Zirconium and yttrium indicate a contribution by stable heavy minerals such as zircon, monazite and xenotime. Titanium is found in a number of different minerals including ilmenite, rutile, and sphene, and can also be found within the structure of certain clay minerals. Vanadium is commonly adsorbed on clay minerals, but is also found in minerals such as chromite, ilmenite, magnetite, and sphene, in which it substitutes for the major cations. Cobalt commonly occurs in sedimentary rocks as an oxide, and may also be adsorbed onto clay minerals. Copper occurs in association with sulphide minerals, and may substitute for cations in mafic minerals.

5.2.4 Approach Used In This Study

In treatment of the data from this study, the aim of the author was to provide the most complete characterisation possible with the available data. This involved aspects of most of the data treatment methods outlined in the previous sections, including: plotting of the major element data on variation diagrams of Bhatia (1983) and Roser and Korsch (1986); plotting of the major element data using the discriminant diagrams of Roser and Korsch (1988); examining relationships between major and trace element data in the manner outlined by Van de Kamp and Leake (1985); and applying the method of factor analysis to trace element data (Hiscott, 1984). In addition, the author has extended the approach of Van de Kamp and Leake (1985) to combine some of the major and trace element data in a factor analysis to better characterise the location of trace elements

within the samples and to test whether statistical methods may be used to relate major and trace element parameters.

5.2.5 Major Element Geochemistry

5.2.5.1 Variation Diagrams From Bhatia (1983)

Sandstones from the Lower Head Formation and Goose Tickle group can be characterised as generally having intermediate silica content (cf. Taylor and McLennan, 1985). In each unit a small number of samples have low silica content, and these tend to be examples of fine grained sands which contain proportionately higher contents of carbonate cement and/or shale chips. A qualitative comparison of the major element data from the Goose Tickle group and Lower Head Formation with the discriminating parameters outlined by Bhatia (1983) shows the following.

Sandstones of the American Tickle formation have high values of $(Fe_2O_3+MgO)\%$ with a mean of 9.16% (standard deviation 2.78) and a range of 2.98% to 15.06%. High values tend to be associated with sandstones which are finer grained and have a higher proportion of carbonate cement and/or shale chips. $TiO_2\%$ has a mean value of 0.51% (s.d. 0.17). The mean Al_2O_3/SiO_2 ratio is 0.13 (s.d. 0.04). K_2O/Na_2O values have a mean of 1.05 (s.d. 0.32). Mainland formation rocks have a mean $(Fe_2O_3+MgO)\%$ of 7.37 (s.d. 1.99), an Al_2O_3/SiO_2 ratio of 0.15 (s.d. 0.18), K_2O/Na_2O of 1.38 (s.d. 0.26) and a mean $TiO_2\%$ of 0.51 (s.d. 0.22). The two formations are rather similar, but they do not conform to any of Bhatia's (1983) provenance categories defined on the basis of major element chemistry. The high $(Fe_2O_3+MgO)\%$ of the

Goose Tickle group should be characteristic (according to Bhatia, 1983) of sandstones derived from an oceanic island arc (American Tickle formation), or a continental island arc (Mainland formation), although the range of values encompasses all provenance types, and comparison with grain size information in Appendix 5 shows a clear grain size effect on the $(Fe_2O_3+MgO)\%$. $TiO_2\%$ values are typical of those derived from a continental island arc, and K_2O/Na_2O values are typical of sandstones derived from an active margin.

The Lower Head Formation displays broadly similar major element chemistry to the Goose Tickle group with an $(Fe_2O_3+MgO)\%$ mean value of 7.60% (s.d. 0.15), Ti% of 0.56% (s.d. 0.15), Al_2O_3/Si_2O_3 of 0.12 (s.d. 0.03) and a K_2O/Na_2O mean value of 1.00 (s.d. 0.29).

Judging by the tectonic setting inferred for the Goose Tickle group and the Lower Head Formation in chapter 3 and the petrographic elements identified in chapter 4, these units should conform most closely to the description 'active continental margin' since they were deposited in a foreland basin; however, examination of Bhatia's (1983) definition of active continental margin shows that he included only Andean type continental margins in this category.

Given the exclusion of foreland basin settings from Bhatia's (1983) study, it should not be surprising that the Goose Tickle group and Lower Head Formation are difficult to categorise using his parameters. In addition, many of the sandstones analysed were coarser than the recommended medium grain size. Despite all of this, some useful information can be derived from plots of major element parameters for the Goose Tickle

group and Lower Head Formation on the variation diagrams suggested by Bhatia (1983).

Mafic and ultramafic sources inferred in chapter 4 are probably responsible for the high iron and magnesium content, whereas the high potassium feldspar content is reflected in a fairly high K_2O to Na_2O ratio. The chemistry may be further complicated by the possibility that reworked older sediments may have contributed a significant proportion of the detritus.

Al_2O_3/SiO_2 vs. $(Fe_2O_3+MgO)\%$ (figure 5.1) shows a positive correlation for all three formations. This is interpreted as a grain size/clay mineral effect, with the finer grain sizes showing a higher Al content (greater proportion of clay minerals) corresponding to a higher $(Fe_2O_3+MgO)\%$, and suggesting that the Fe and Mg is largely concentrated in clay minerals for all three formations. The narrower range of $(Fe_2O_3+MgO)\%$ for the Lower Head Formation is interpreted to reflect the narrower range of grain sizes analysed for this formation. A similar trend is shown in the plot of $TiO_2\%$ vs. $(Fe_2O_3+MgO)\%$, again suggesting that the concentration of $TiO_2\%$ is partly grain size dependent (figure 5.2).

The plot of K_2O/Na_2O vs. $(Fe_2O_3+MgO)\%$ (figure 5.3) shows a distinct difference between the Lower Head Formation and the Goose Tickle group. The Lower Head Formation shows a very wide range of K_2O/Na_2O reflecting the variable plagioclase/total feldspar ratio from sample to sample. The American Tickle formation shows considerable scatter, reflecting both a wide range of $(Fe_2O_3+MgO)\%$ (a grain size effect), and a fairly wide range in K_2O/Na_2O, although the overall K_2O/Na_2O ratio is lower than for the Lower Head Formation. The Mainland formation shows a more

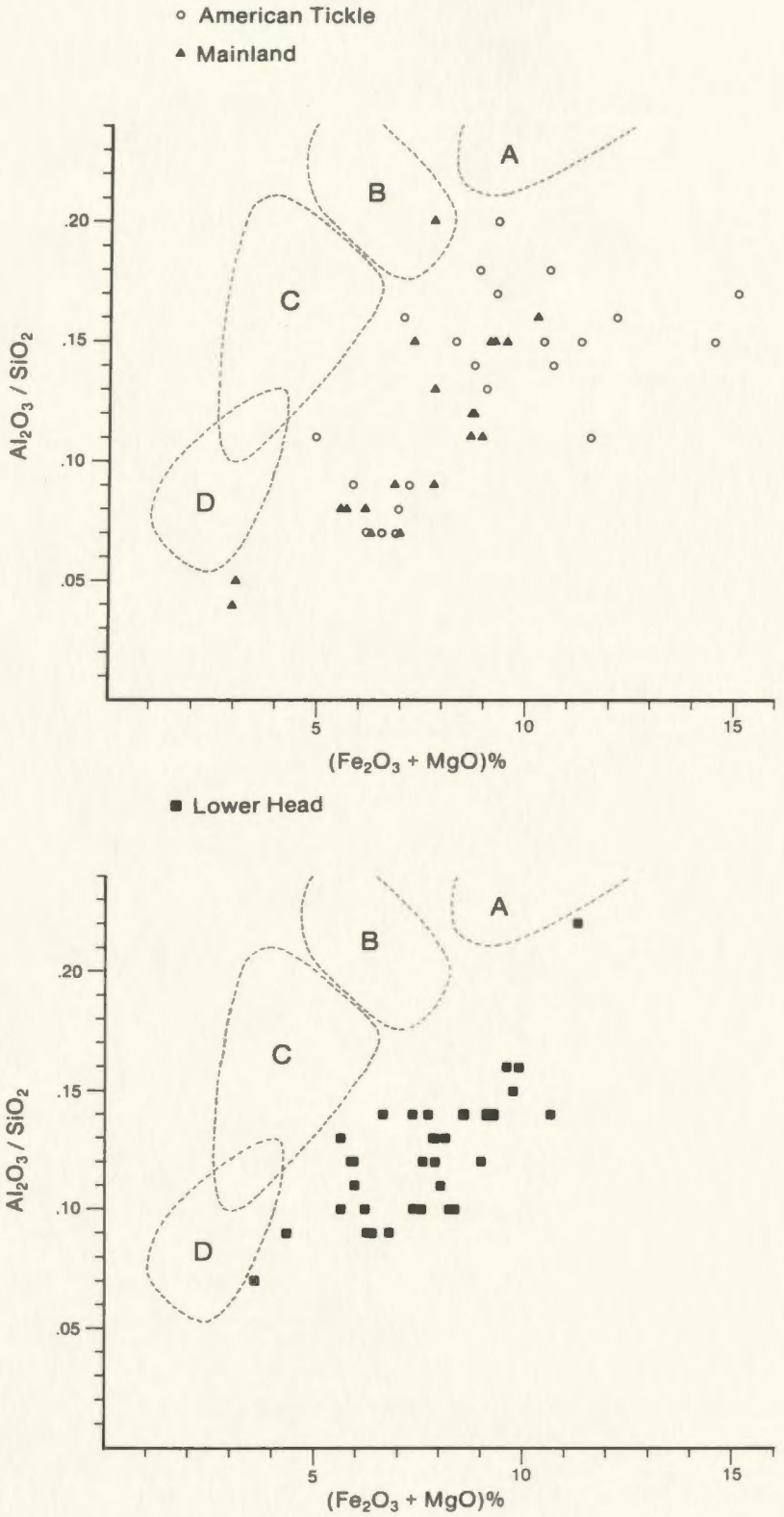


Figure 5.1: Plot of Al_2O_3/SiO_2 vs. $(Fe_2O_3+MgO)\%$ for the Goose Tickle group and Lower Head Formation. Fields after Bhatia (1983). A=Oceanic Island Arc. B=Continental Island Arc. C=Active Continental Margin. D=Passive Margin.

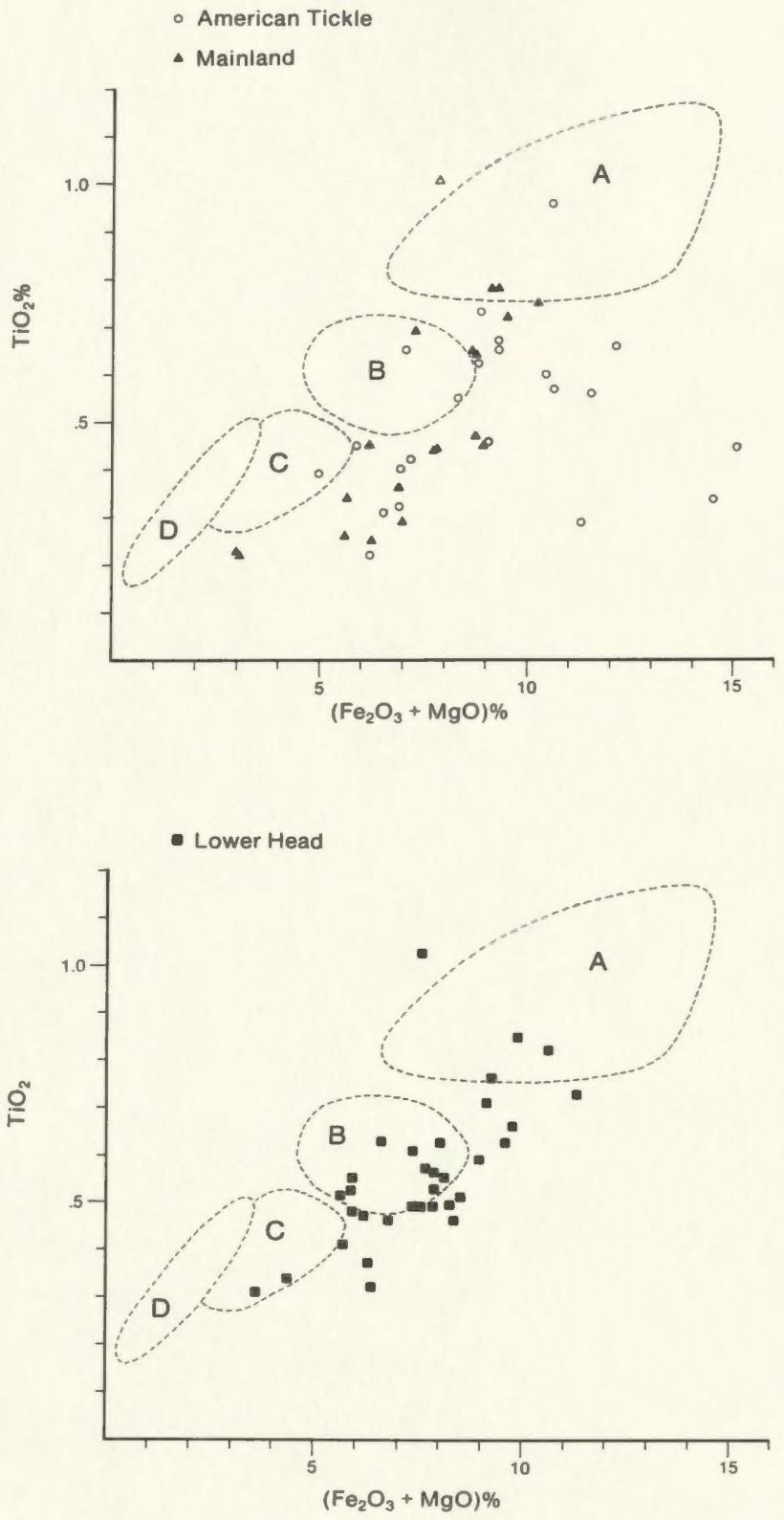


Figure 5.2: Plot of TiO_2% vs.(Fe_2O_3+MgO)% for the Goose Tickle group and Lower Head Formation. Fields keyed as in figure 5.1.

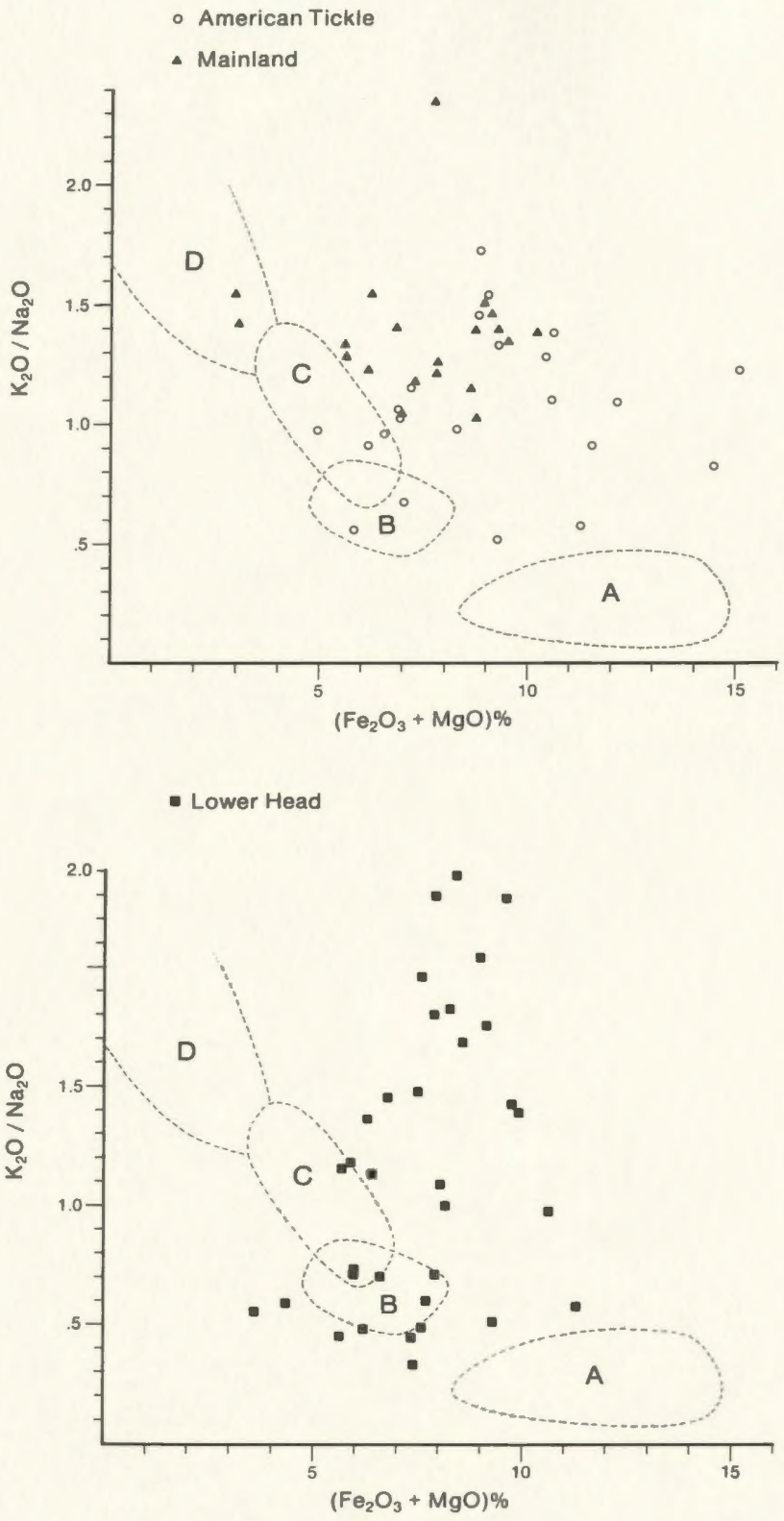


Figure 5.3: Plot of K_2O/Na_2O vs. $(Fe_2O_3+MgO)\%$ for the Goose Tickle group and Lower Head Formation. Fields keyed as for figure 5.1.

restricted range of $(Fe_2O_3+MgO)\%$ and K_2O/Na_2O. The diagram of $Al_2O_3/(CaO+Na_2O)$ vs. $(Fe_2O_3+MgO)\%$ (figure 5.4) is difficult to interpret, but shows a very wide variation of $Al_2O_3/(CaO+Na_2O)$ for the Lower Head Formation, possibly again related to the variation from sample to sample in proportions of different types of feldspars.

It is abundantly clear that the sandstones of the Goose Tickle group and Lower Head Formation bear no relation chemically to any of the fields outlined by Bhatia (1983), and the effect of grain size, probably even within the range alluded to by Bhatia (1983), is significant.

5.2.5.2 Variation Diagrams From Roser and Korsch (1986)

Roser and Korsch's (1986) paper resorted to the simpler approach of discrimination of three broad fields based solely on a plot of K_2O/Na_2O vs. $SiO_2\%$. Analyses of sandstones of the Lower Head Formation and Goose Tickle group are plotted on figures 5.5 and 5.6, with Roser and Korsch's (1986) fields shown. Sandstones of both units generally straddle the boundary between the passive margin and active margin fields. Several of the samples, however, plot in the arc field, because they contain low $SiO_2\%$ as a result of their high carbonate cement content. Although it is not clear how much of this carbonate is of biogenic origin, it can be inferred from the discussion in chapter 4 that at least some of it is derived from dissolution of carbonate rock fragments and is hence ultimately of biogenic origin. Roser and Korsch (1986) accommodated this problem by recalculating the major element parameters to 100% volatile and CaO free, and by correspondingly recalculating the field boundaries. The Lower Head Formation

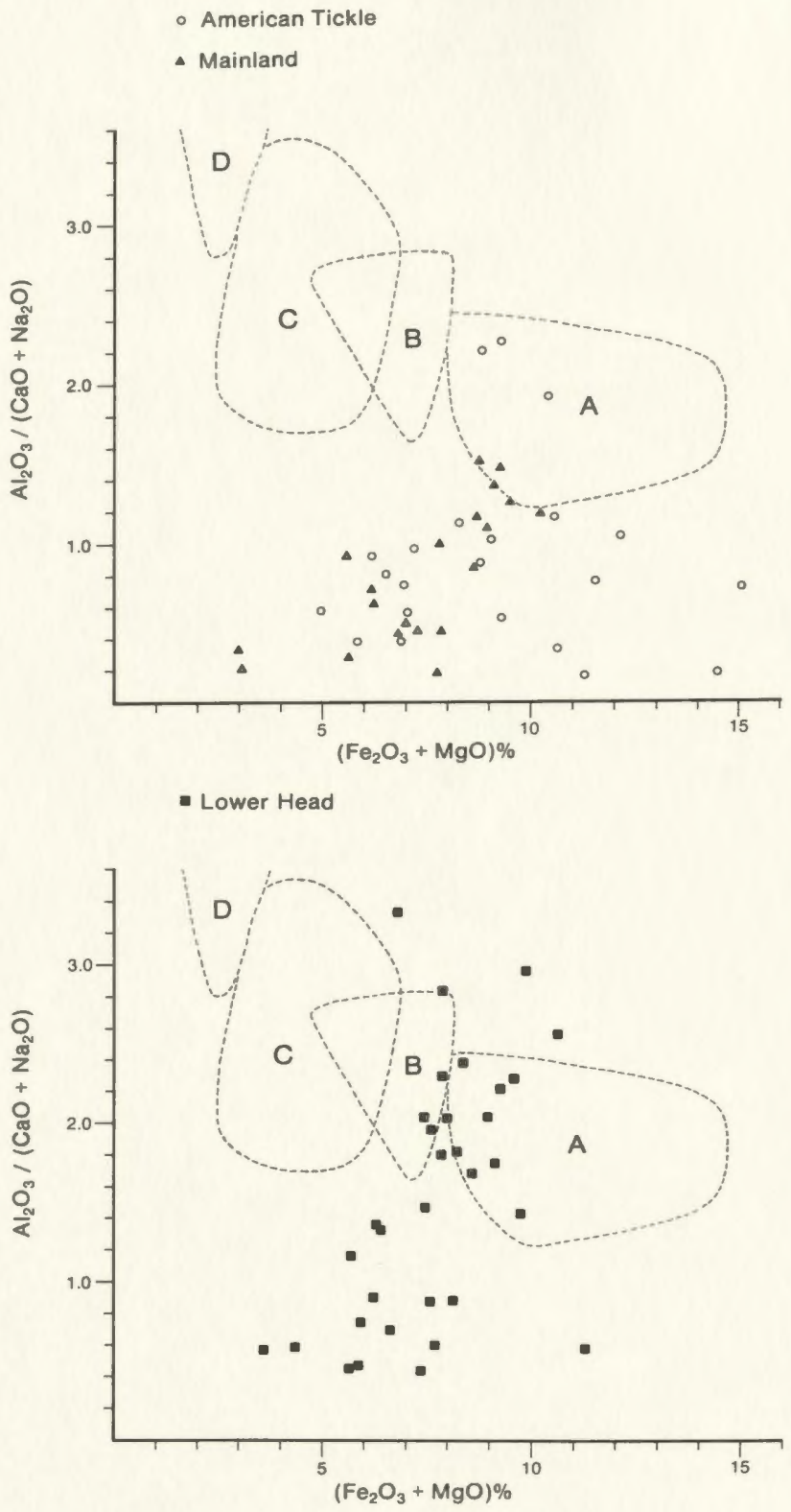


Figure 5.4: Plot of $Al_2O_3/(CaO+Na_2O)$ vs. (Fe_2O_3+MgO)% for the Goose Tickle group and Lower Head Formation. Fields keyed as in figure 5.1.

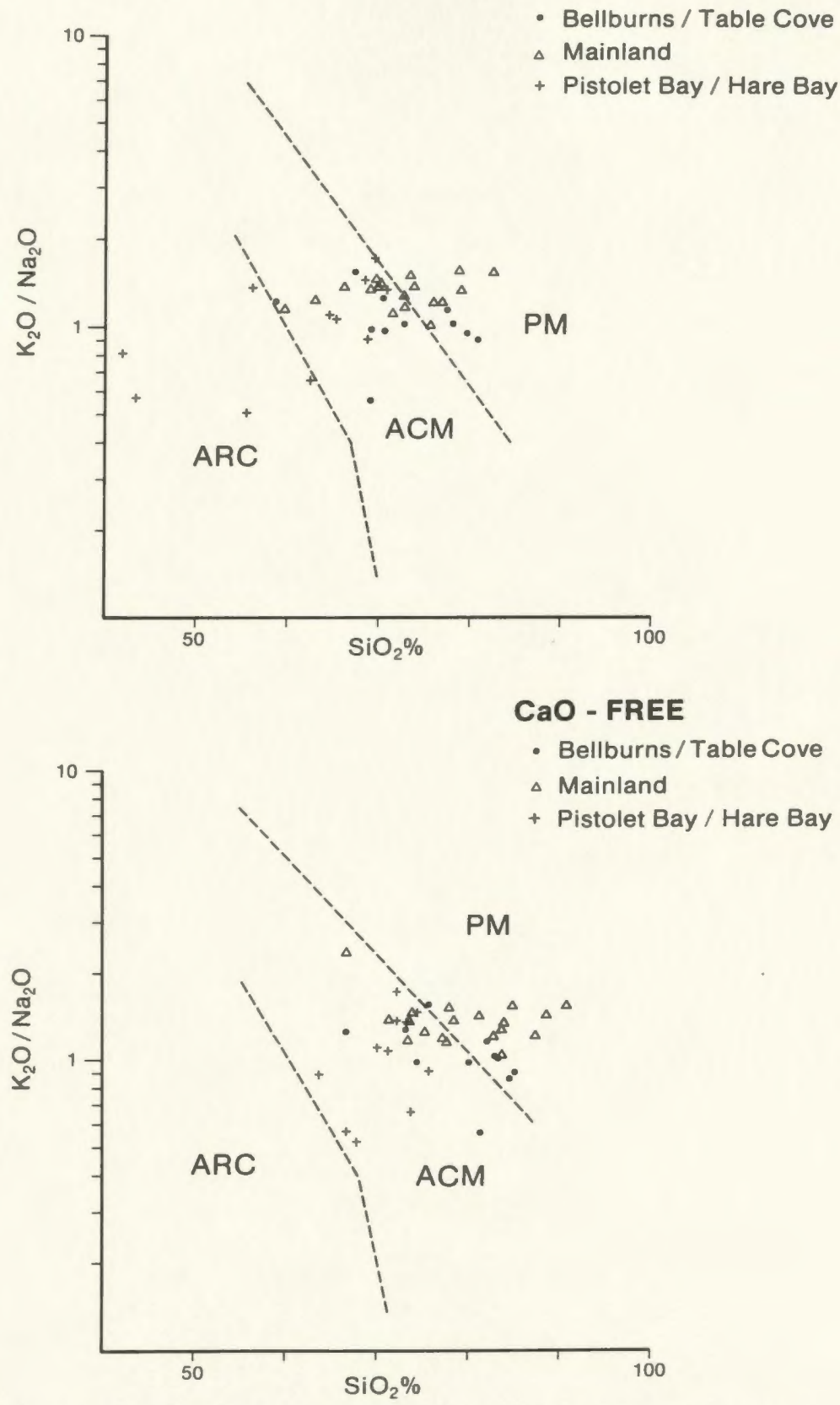


Figure 5.5: Plot of K_2O/Na_2O vs. $SiO_2\%$ for the Goose Tickle group. Lower diagram plots values recalculated to 100% CaO and volatile free. Fields after Roser and Korsch (1986). ARC=arc. ACM=Active Margin. PM=Passive Margin.

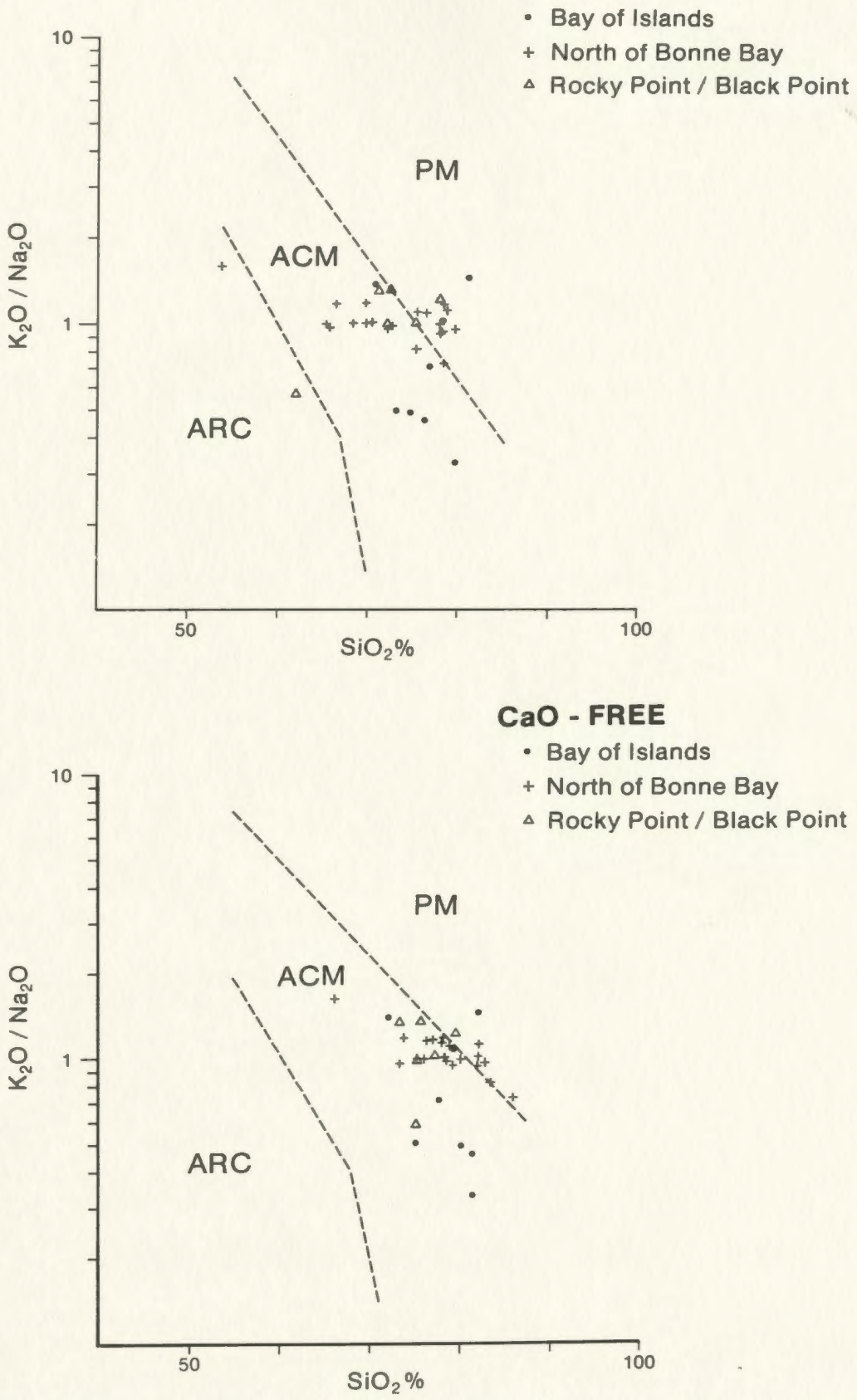


Figure 5.6: Plot of K_2O/Na_2O vs. SiO_2% for the Lower Head Formation. Lower diagram plots values recalculated to 100% CaO and volatile free. Fields as in figure 5.5.

and Goose Tickle group samples are shown plotted individually on a diagram revised in this manner with all samples now plotting in the active or passive margin fields.

Since there is abundant independent evidence to show that the Lower Head Formation and Goose Tickle group were deposited in an 'active margin' setting, the plotting of a significant number of samples, particularly from the Mainland formation, in the passive margin field, must be addressed. There are three possible hypotheses to explain this observation:

1. Most of the sands which plot in the passive margin field are from the Mainland formation, and several of those from near the inferred top of the section are particularly rich in silica. It is possible that towards the top of the Mainland formation a gradual change in provenance to a source richer in silica occurs, as originally suggested by Schillereff and Williams (1979). However, this hypothesis is not favoured because not all of the silica rich sands occur at the top of the section and in addition, sandstones from units stratigraphically above the Mainland formation show a similar scatter on either side of the passive/active margin boundary, although admittedly the data are sparse (see chapter 6, figure 6.11);

2. A facies variation may be responsible for the chemical variation. The Mainland formation, particularly near its top, is characterised by several coarse and very coarse grained sands which have clearly been reworked and have had some of the fine material removed. Carbonate cement is common in these better sorted arenites and may be

replacive, particularly of feldspars. This may have affected the K_2O/Na_2O ratio in a complex way. Although this cannot be tested in a rigorous fashion with the data available, an inspection of appendix 5.3 shows that the expected relationship is shown in several of the coarse samples. Feldspar dissolution and replacement by calcite is particularly evident in the thin section of sample ML 26 and the effect on bulk chemistry is clear. Aluminium has presumably been removed from the system during the process of diagenesis, and silica has increased correspondingly.

Thus the observed trend on the Roser and Korsch (1986) diagrams may be have been caused by a combination of mode of deposition, diagenesis, and the closure effect;

3. The chemical signature of the source is responsible for the fact that many samples plot in the passive margin field. It has already been suggested that much of the siliciclastic detritus in the Lower Head Formation and Goose Tickle group may be recycled passive margin sediments.

It is likely that a combination of the latter two hypotheses can best explain the marked passive margin 'affinity' of the Lower Head Formation and Goose Tickle group.

5.2.5.3 Discrimination Diagrams of Roser and Korsch (1988)

Sandstones of the Goose Tickle group and Lower Head Formation were treated in the manner outlined by Roser and Korsch (1988), to try to determine whether a dominant source (basalt, andesite, felsic, recycled) could be identified chemically in these

units. Thus discriminant scores were calculated for major element parameters, which in this case were ratios of major element oxides to Al_2O_3. The ratios were used rather than the individual oxide percentages, because (as discussed above) there may be biogenic carbonate in some of the samples, and Roser and Korsch (1988) designed the ratio discriminant functions to minimise the effect of biogenic carbonate.

The discriminant scores, once calculated, were plotted on the territorial plot of Roser and Korsch (1988) (figures 5.7 and 5.8), but it was found that many of the samples did not plot on the diagram, principally because of high loadings on magnesium. This was particularly true for fine grained samples of the Goose Tickle group. Extrapolation of the fields of Roser and Korsch (1988) shows the sandstones plotting partly on Plext, which is a zone where P1 (basalt) and P4 (recycled) fields overlap, and partly on P4. Roser and Korsch (1988) were forced to construct Plext because certain of their samples which were clearly of mafic origin, plotted in the P4 (recycled) field. Roser and Korsch (1988) stated that the overlap arose because the samples used to construct their discriminant functions and hence their territorial plot did not contain sufficient representatives of sandstones derived from magnesian-rich mafic rocks. The fact that the samples from this study require extrapolation of Roser and Korsch's (1988) fields as a result of high loading on magnesium may indicate a strong chemical signature from an ultramafic or mafic source.

Roser and Korsch (1988) considered it unlikely that samples derived from a mafic source could be confused with those from a recycled source. It appears in this case that one cannot determine the extent of a recycled sedimentary source, since the signature of

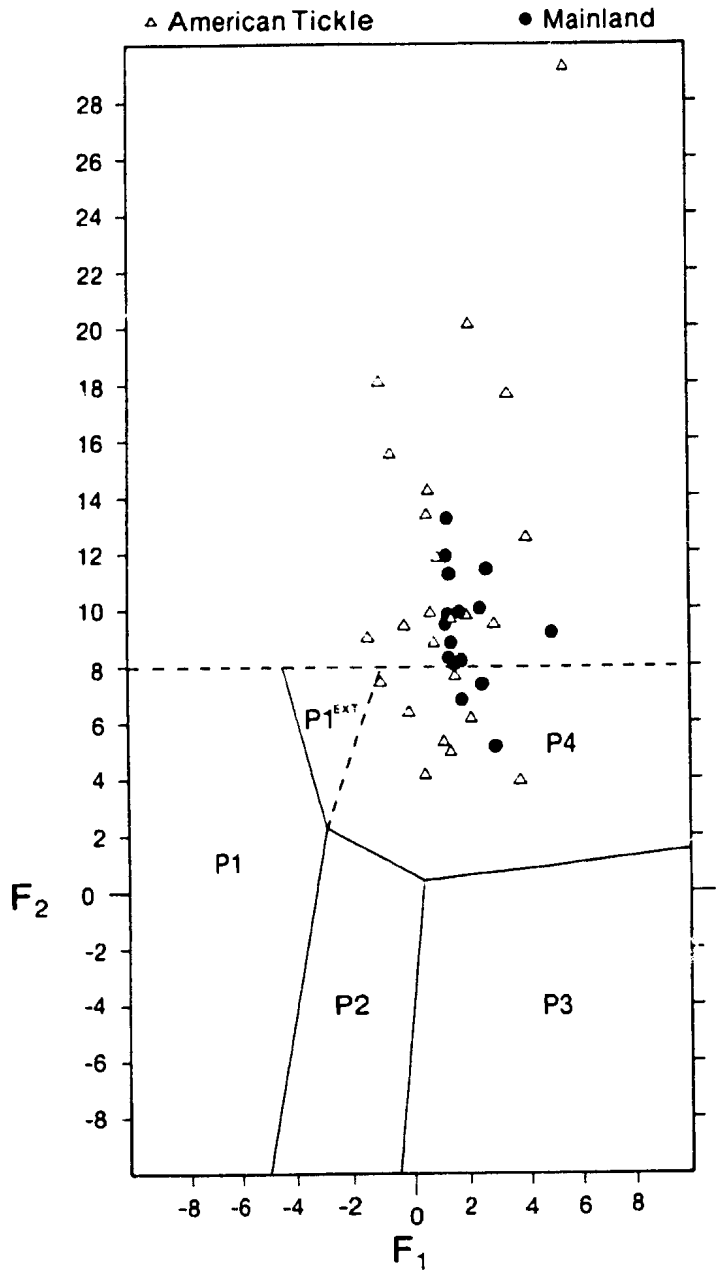


Figure 5.7: Discriminant plot of major element parameters, Goose Tickle Group. Fields after Roser and Korsch (1988). P1=mainly basaltic. P2=mainly intermediate. P3=mainly felsic. P4=mainly recycled. See text for explanation of P4ext.

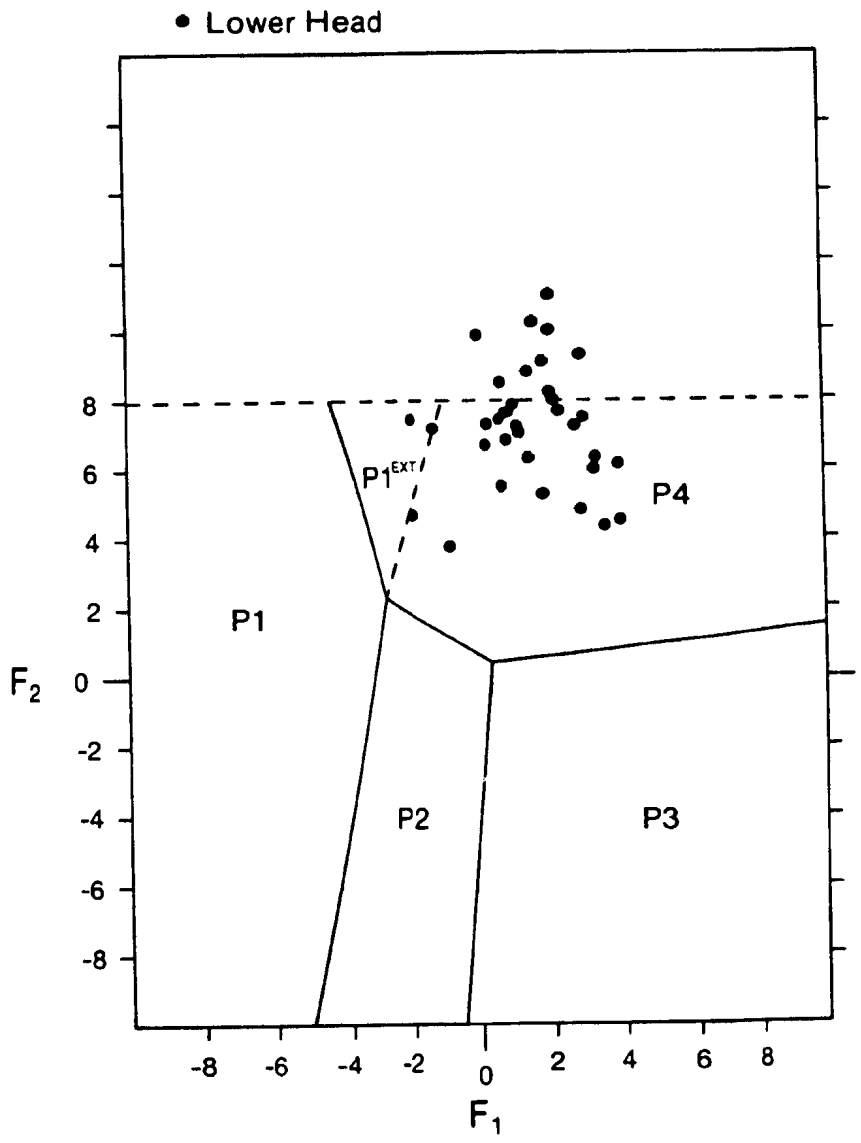


Figure 5.8: Discriminant plot of major element parameters, Lower Head Formation. Fields are keyed as in figure 5.7.

the ultramafic/mafic source prevents this from clearly being identified. However in general both units would tend to plot on an extrapolated P4 as a result of the F1 scores, suggesting that a recycled source did contribute.

The investigation detailed above suggests that it is unlikely that discrimination diagrams have much application in the study of the geochemistry of sandstones from a mixed source, since a dominant chemical signature cannot be identified. It is also notable that a grain size effect seems marked in these samples, whereas Roser and Korsch (1988) claim that the grain size effect is minimised by the use of these discrimination diagrams.

5.2.5.4 Major Element Geochemistry - Discussion

This study of major element geochemistry has shown a number of things. Firstly, a mafic or ultramafic source is suggested by the behaviour of magnesium. Secondly, although this signature prevents the clear distinction of any others, several of the approaches utilised suggest input from a recycled passive margin source. Although these observations are not surprising given the petrographic characteristics described in chapter 4, they would be far more difficult to interpret in the absence of petrography. This indicates the inadvisability of carrying out geochemical investigations without supporting petrography.

In addition, it is clear that grain size has had a major effect on chemistry, and for these samples none of the methods discussed above can successfully overcome the grain size effect, which is ultimately a consequence of mode of deposition.

Mode of deposition determines not only grain size, but proportion of matrix (where elements such as aluminium may be abundant) and initial porosity and permeability of the sediment. Primary porosity and permeability will influence diagenetic reactions by providing pathways for addition or removal of elements. The effects of all of these factors can be observed in the major element geochemistry of the Goose Tickle group and Lower Head Formation. Far more attention should be paid to the overall sedimentology if major elements are to be used successfully in provenance investigations.

5.2.6 Trace Element Geochemistry

Trace element geochemistry has largely been addressed using methods similar to those of Van de Kamp and Leake (1985). This means that trace elements have been considered in terms both of their relationships to each other and also to major elements.

5.2.6.1 Grain Size and al-alk

It is clear from the discussion of major element geochemistry that it is important to be able to evaluate grain size effects when studying the chemistry of sandstones. As outlined in the discussion at the beginning of this chapter, the parameter al-alk can be used for this purpose.

For data acquired in this study, a number of cautionary factors regarding al-alk must be taken into account. Clay minerals in the Lower Head Formation and Goose Tickle group arenites have two origins: firstly detrital and secondary clay matrix, which by definition is fine grained; and secondly large grains of detrital chlorite, some of which

are presumably altered serpentine. An increase in al-alk generally indicates an increase in the amount of sheet silicate material within the sample population and hence is often correlated with decreasing grain sizes. The samples from this study contain significant sand-sized grains of sheet silicate, and an increase in al-alk cannot be automatically assumed to be related to a decrease in grain size. Also, some finer grained samples contain carbonate cement which has replaced the clay minerals to a considerable extent. However, an inspection of the data tables in appendix 5 shows that, in general, fine grained samples do have higher al-alk, and the expected relationship is preserved even in these rather unusual samples.

Both the Lower Head Formation and the Goose Tickle group show low overall al-alk values in comparison with those quoted by Van de Kamp and Leake (1985). This could indicate the presence of serpentine, as serpentine does not contain aluminium. Al-alk is also controlled by the compositions of the feldspars. An abundance of calcium rich feldspars and/or mica will result in high values of al-alk, whereas a paucity of calcium rich feldspars mav result in lower values of al-alk (Van de Kamp and Leake, 1985). As discussed in chapter 4, serpentine, if present at all, is in insufficient quantities to affect the major element chemistry. Thus the low overall values of al-alk are interpreted to reflect the dearth of calcium-rich feldspars, which has been demonstrated in chapter 4. Low al-alk in some individual samples, as discussed above, is attributed to replacement of feldspars or clay matrix by carbonate.

5.2.6.2 Correlation Matrices

Van de Kamp and Leake (1985) demonstrated correlations by plotting a very large number of graphs showing relationships between various key major and trace element parameters. A more complete way of achieving the same goal is to construct a table of correlation coefficients for all Niggli parameters and trace elements. These were calculated for the Lower Head Formation and the Goose Tickle group using the statistics program SAS version 6.01. The results are presented in appendix 6. Variables which were below detection limits in all samples were omitted from the tabulation. Certain variables were below the detection limit for some individual samples only. In these cases values for the variables were set to detection limits to avoid effects produced by artificially low values. This follows the approach by Weber and Davis (1991) but it does lead to some anomalous results, notably the failure of Tb to behave similarly to the other rare earth elements, because in a relatively large number of cases Tb is below the detection limit. SAS does not include in the tabulation any samples with missing values.

5.2.6.3 Correlation Matrix for the Goose Tickle group

In the Goose Tickle group the correlation between fm (a measure of the ferromagnesian content) and al-alk is moderate (0.72), and there is similarly a moderate correlation between Niggli ti and al-alk, indicating that titanium and the ferromagnesian elements are largely, but not exclusively concentrated in clay minerals, probably mainly chlorite.

There is a strong negative correlation between al-alk and CaO%, as well as Niggli fm and CaO%, indicative of the fact that carbonate replaces clay minerals, and that some samples which have high amounts of carbonate cement, were reworked and were poor in clay minerals to begin with. Interestingly, Niggli Mg does not show a similar relationship with CaO, suggesting that Mg is present in carbonates to some extent.

The weak correlation between niggli k and al-alk and between K_2O% and Ba suggests that potassium in these rocks occurs both in potassium feldspar and in clay minerals. If potassium feldspar were completely responsible for the variation in k then there would be a strong positive correlation between K_2O% and Ba, and if clay minerals were completely responsible there would be a strong positive correlation between k and al-alk. The hypothesis that Ba is partly associated with potassium feldspar is supported by the barium contents recorded in probe analyses of potassium feldspars (see chapter 4).

Al-alk is only weakly correlated with the rare-earth elements and zirconium, suggesting that these elements are not only present in clay minerals but also in the heavy mineral fraction. Vanadium is also moderately correlated with al-alk.

Niggli mg does not show a marked correlation with any other parameter. The mean value of mg is moderately high, but the maximum value is very high (0.83), as are mean absolute values for Cr and Ni. These features were considered by Van de Kamp and Leake (1985) as indicative of input from an ultramafic source. Chromium is, however, only weakly correlated with nickel (0.69). This will be discussed below.

5.2.6.4 Correlation Matrix for the Lower Head Formation

In the Lower Head Formation al-alk shows a weak positive correlation with ti (0.66) and a strong positive correlation with fm (0.91). These relationships suggest that ferromagnesian elements are strongly related to the presence of clay minerals. Titanium shows some association with clay minerals but the weakness of the correlation is compatible with the fact that Ti is also present in opaque ti oxides and sphene.

Al-alk is strongly negatively correlated (-0.82) with CaO% which indicates the absence of clay minerals where carbonate cement is abundant. Again, the relationships between K_2O%, Ba, and al-alk indicate that potassium is housed both within clay minerals and in potassium feldspar.

Al-alk is very weakly correlated with Co, Cu, Ni and V, suggesting that these elements are present at least partly in association with clay minerals.

Chromium shows no correlation with al-alk but is strongly positively correlated with Zr (0.85), suggesting that both elements are present in the heavy mineral fraction. Niggli mg is not strongly positively correlated with any parameter, but is weakly negatively correlated with all of the rare earth elements and zirconium. Niggli Mg is moderately negatively correlated with strontium.

Chromium, nickel and Niggli mg are higher than the average reported by Van de Kamp and Leake (1985) again suggesting a contribution by an ultramafic source.

5.2.6.5 Comparisons Between the Goose Tickle group and the Lower Head Formation

The main differences between the Lower Head Formation and the Goose Tickle

group are that the Lower Head Formation displays stronger relationships between the pairs chromium/zirconium and fm/al-alk, and displays a poorer correlation between nickel and chromium. Mean absolute values of chromium and nickel are higher in the Goose Tickle group than in the Lower Head Formation, although the standard deviations about the mean are very high and overlap between the two units.

These findings would be consistent with the increasing importance through time for an ultramafic source (which may partly be masked by grain size effects), however, they contrast with the findings for shales interbedded with the sandstones (Garver, 1991 pers. comm.) where the average values of chromium and nickel in allochthonous shales are higher than those in parautochthonous shales.

Neither the Goose Tickle group nor the Lower Head Formation preserves igneous trends as described by Van de Kamp and Leake (1985), as there is no negative correlation between Niggli mg and Niggli si, Cr and Ni do not correlate well with Niggli mg, and there is no negative correlation of Ni with al-alk. The rocks are enriched in silica with respect to Niggli mg despite the high overall values of mg, indicating that the chemical signature is dominated by a sedimentary influence. Thus the sandstones do not plot in the field typical of igneous rocks as outlined by Van de Kamp and Leake (1985) (see figure 5.9).

Chromium in both units shows a relatively weak relationship with Ni, which is in striking contrast to the behaviour of Cr and Ni in shales interbedded with the Goose Tickle group and Lower Head Formation (Garver pers. comm. 1990) where the correlation coefficient between Cr and Ni is 0.95.

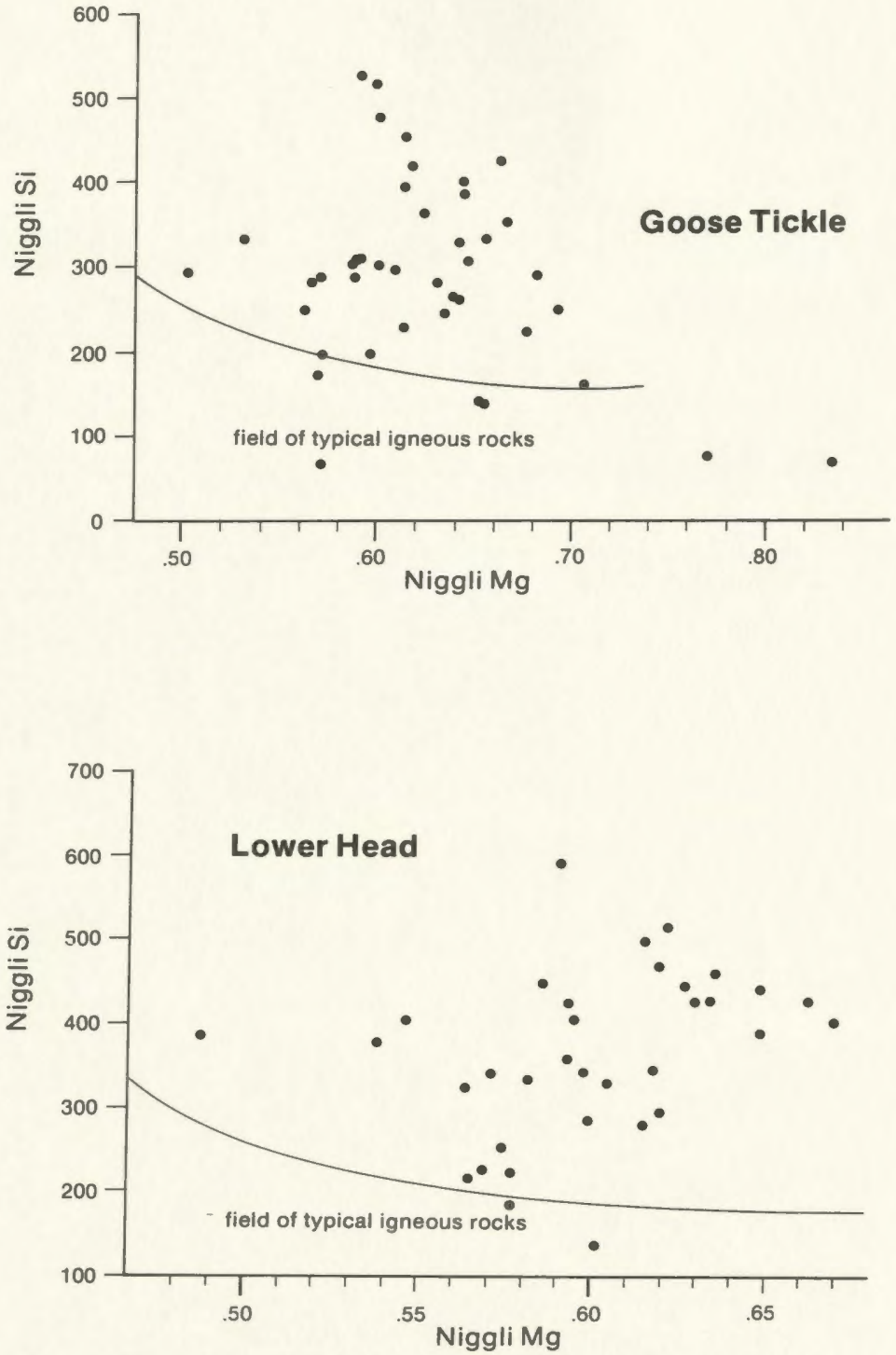


Figure 5.9: Plot of Niggli Mg vs. Niggli Si for the Goose Tickle group and the Lower Head Formation. Fields after Van de Kamp and Leake (1985).

The lack of clear correlation in both units of Cr with Niggli mg may be indicative of the fact that Cr is contained in opaque oxides, as a chromium spinel, and is also present in chlorite or adsorbed on clay minerals. Normally, a dominance of chromium oxides will result in a negative correlation with Niggli mg, whereas its presence in mafic silicates will result in a positive correlation with Niggli mg (Van de Kamp and Leake, 1985).

The behaviour of Niggli mg is problematic because of its tendency not to vary with any other parameter. However, it shows a moderate negative correlation with Sr in the Lower Head Formation, whereas it shows a very weak positive correlation with Sr in the Goose Tickle group. In the Goose Tickle group, Sr shows a weak correlation with CaO%, thus reinforcing the suggestion that an original trend for Mg has been obscured by a complex association of magnesium with carbonate cement.

Rare Earth Elements in the Goose Tickle Group are strongly correlated with K_2O%, whereas in the Lower Head Formation there is virtually no correlation. This relationship is problematic and will be the subject of a later investigation.

The inspection of the correlation matrices shows clearly that despite some similarities, the Lower Head Formation and Goose Tickle group are chemically distinct. Whether these differences are entirely a result of provenance variation is less easy to determine, but the complex behaviour of Niggli mg does suggest that diagenesis may have been a factor in determining the differing chemistry of each unit.

5.2.6.6 R-factor Analysis

The correlation matrices described above can clearly provide useful information, but such large matrices are unwieldy, and reduction of the data to a number of underlying factors, if possible, seems desirable. R-factor analyses of the Goose Tickle group and the Lower Head Formation were conducted separately using the procedure FACTOR in SAS 6.01 (SAS/STAT Users Guide, 1988). The mathematics of the method is thoroughly described in Davis (1986) and the specifics of the procedure FACTOR are detailed in the SAS/STAT users guide (1988). The factors were then subjected to varimax rotation (e.g. Davis, 1986) to aid in interpretation. For each set of samples the software was instructed to calculate Kaiser's Measure of Sampling Adequacy to determine the acceptability of the data (SAS/STAT Users Guide, 1988).

For each sedimentary unit, two sets of parameters were analysed. The first group includes al-alk, Niggli ti, Niggli fm, Zr, Cu, Ni, Co, and Cr and represents an attempt to relate the behaviour of key trace elements to that of major elements (see introduction to this chapter). Initially an attempt was made to include Niggli mg, but measures of adequacy were far below acceptable levels, as Niggli mg does not show a strong tendency to vary with any other parameter.

5.2.6.7 R-factor Analysis for the Goose Tickle group

For the Goose Tickle group, the overall sampling adequacies were acceptable (>0.5) but the individual value for Cr was not. Three factors were isolated (see appendix 6). The first factor of the rotated set contains strong loadings on Zr and Niggli

ti, with moderate loadings on al-alk, Cu and Co, and is interpreted to reflect a heavy/mafic mineral factor. The loading on al-alk for this factor would indicate the presence of heavy minerals containing aluminium, such as garnet, biotite, and chlorite. Zirconium and Ti are probably present in the heavy minerals zircon, rutile and sphene, all of which have been observed in the Goose Tickle group, and Cu and Co may substitute in the structures of the mafic minerals.

The second factor exhibits high loadings on fm and al-alk, and moderate loadings on Cu, Ni, Co, and Niggli ti., and is interpreted as a clay mineral factor. This indicates that ferromagnesian elements and copper, nickel, cobalt, and titanium are associated with clay minerals, probably mainly chlorite.

The third factor is characterised by strong loadings on chromium, nickel, and to a lesser extent cobalt and copper, and would, according to Hiscott (1984) and Garver (pers. comm. 1992) be interpreted as an ultramafic factor.

The second group of parameters which was factor analysed for the Goose Tickle group was the group Niggli ti, Zr, Y, Cu, Ni, V, Co, and Cr, which is a similar set of parameters to those analysed by Hiscott (1984) (with the exception of cobalt). Sampling measures were adequate for this group of parameters. The rotated factor pattern involves one factor with strong loadings on Zr, Niggli ti, and Y, and lesser loadings on V, Co and Cu. This is interpreted as the heavy mineral factor analogous to that described above. Yttrium is commonly found in some quantities in zircon, and may also be associated with the minerals xenotime (which has not been identified in the Goose Tickle group) and monazite (which has been found in the Goose Tickle group). Vanadium is commonly

found in some quantity in sphene.

The second factor displays strong loadings on Cr and Ni, with a smaller loading on copper, and is interpreted as the ultramafic factor. The third factor shows strong loadings on V and Co, with lesser loadings on Ni and Niggli ti and is interpreted as the clay mineral factor.

Although factor analyses of the two groups show essentially the same results, it is clearly much easier to distinguish the clay mineral from the mafic mineral factor if major element parameters are involved in the analysis.

5.2.6.8 R-factor Analysis for the Lower Head Formation

For the Lower Head Formation, the same sets of parameters as for the Goose Tickle group were factor analysed. The overall sampling adequacy was acceptable, but the individual sampling adequacies for zirconium and chromium were not acceptable, therefore results for the Lower Head Formation cannot be considered statistically rigorous. However, factor analysis does seem to bear out the relationships which can be deduced based on an inspection of the correlation matrix.

The first group of parameters discussed is the group which includes major element parameters. The first factor shows a very strong loading on Zr and Cr, with a moderate loading on Niggli ti and would be interpreted as a heavy mineral factor. The second and third factors have moderate loadings on al-alk. The second factor, with strong loadings on fm and moderate loadings on Ni and Niggli ti is interpreted as a clay mineral factor. The third factor with its fairly strong loadings on copper, cobalt, and moderate loadings

on ti and fm is interpreted as a mafic mineral factor. A fourth factor is regarded as an artifact of the unsuitability of the data for this treatment.

Sampling adequacies on the trace element data for the Lower Head formation were below acceptable levels both overall and individually for Ni, Zr, V, and Y. The first of the rotated factors contains a strong loading on Cr, Zr, and Niggli ti, mimicing the results found for the previous group of parameters and is therefore interpreted as a heavy mineral factor. The second factor would again be interpreted as a mafic mineral factor, and the third factor again is interpreted as a clay mineral factor. Nickel and vanadium in this case show a strong loading on a fourth, less important factor, which may be related to the presence of diagenetic pentlandite in some of the sediments (Botsford, 1988), or may be an artifact of the inadequacy of the data.

5.2.6.9 R-factor Analysis - Discussion

R factor analysis, although not completely satisfactory for the small numbers of samples available, does seem to support the observation made by inspection of the correlation matrices that chromium in the Lower Head Formation is concentrated in heavy minerals, and is not related in its behaviour to nickel, whereas in the Goose Tickle Group, chromium shows a stronger relationship to nickel and many elements show a stronger correlation to al-alk.

5.2.6.10 The Ultramafic Factor - Discussion

The behaviour of Cr and Ni as indicators of an ultramafic source should now be

discussed, since the isolation above of an 'ultramafic factor' for the Goose Tickle group does not address the question of where in the sandstone framework these elements are housed, or why Cr behaves differently in the Lower Head Formation.

As discussed in the introduction to this chapter, Cr and Ni may occur in a number of different minerals. It is clear from chapter 4 that Cr and Ni may occur in significant amounts in chlorites, but that their relationship to each other in the examples of this mineral probed shows no readily observable pattern. The major mineral in which Cr is usually assumed to reside is chromite, where Cr_2O_3 may constitute up to 50% of the total weight of the mineral. Chromite grains have certainly been identified in heavy mineral layers in Goose Tickle group, yet the element Cr does not show a correlation with the other heavy mineral tracer elements such as Zr. In addition, Ni is present in chromite only in very small proportions, and yet Ni and Cr show a moderate correlation in Goose Tickle group sandstones and a very strong correlation in shales (Garver, pers. comm. 1991).

The answer to these questions may lie in the fact that Cr and Ni may be adsorbed on clay minerals as well as substituting directly within the clay mineral structure. It is here postulated that the adsorption effect may not vary in response to the proportion of clay minerals present in the sample, but in response to the abundance of Cr and Ni ions in the dissolved load supplied along with the sediment load. Thus it is suggested that a greater amount of Cr and Ni was supplied in the dissolved load to the Goose Tickle group, and it is this factor which is commonly identified as the ultramafic factor. It is unclear why Cr would not show some variation with the tracer elements for heavy

minerals, but it is possible that an increase in physical supply of chromite correlates with an increased supply of dissolved Cr and Ni ions thus masking any tendency of chromium to behave similarly to other heavy mineral elements.

A factor analysis of trace element parameters from all of the sandstones, Goose Tickle group and Lower Head Formation combined was carried out (not shown in appendix 6) to see if the ultramafic factor could be identified in the combined group of samples. The results are not reproduced here as they are not substantially different from those outlined above, and despite the larger number of samples, which should have been adequate, some sampling adequacies were not acceptable. For the combined set of samples, the loading shown by Cr on the heavy mineral factor is very small. The number of samples of Goose Tickle group in this analysis only slightly exceeded the number of samples of Lower Head Formation, and the behaviour of Cr in the combined analysis suggests that the 'ultramafic factor' may mask the tendency of Cr to behave with the other heavy minerals. This may explain why Hiscott (1984) did not observe a relationship such as that observed in the Lower Head Formation, as the number of autochthonous sandstones analysed by Hiscott (1984) outnumbered the allochthonous sandstones by 29.

An increased supply of Cr and Ni ions in the dissolved load might imply a greater intensity of weathering and breakdown of mafic minerals in the source area of the Goose Tickle group relative to the Lower Head Formation. This hypothesis may be supported by the (admittedly rather sparse) evidence from probing of chlorites (chapter 4), that the highest values of Cr and Ni implying the greatest degree of alteration of mafic and

ultramafic minerals were seen in chlorites of the Goose Tickle group. Possible independent evidence for intense weathering conditions in the Llanvirn has been provided by Casey and Kidd (1981) who observed a strongly hematised weathering profile on the Bay of Islands Ophiolite, which they infer to have been exposed in the Llanvirn.

5.2.6.11 Utility of Factor Analysis

Clearly, the inclusion of major element parameters in a factor analysed group above does not substantially affect the perceived relationship between trace elements, and hence the inclusion of major elements in the factor analysis can aid considerably in the interpretation of trace element behaviour. Al-alk, in this particular case, allows for an easier distinction between the clay mineral and mafic mineral factors.

It is also clear that distinctions may be made between the behaviour of elements in different units using the general method of Van de Kamp and Leake (1985) and using factor analysis, if variables are chosen carefully and if sufficient numbers of samples are included in the analysis. Thus the methods may have significance in detailed local studies as well as in the more regional studies envisioned by Hiscott (1984) and Garver (pers. comm. 1991). Interpretations must be made with reference to sandstone petrography, however, and in this context it is clear that comment cannot be made on the high values of Cr and Ni recorded by Garver (pers. comm. 1991) in the shales of the Lower Head Formation. Botsford (1988) has suggested that Cr is present in these shales in silt sized grains of chromite, whereas Ni is present in pentlandite, which Botsford (1988) interpreted as being of diagenetic origin. How the petrography of these shales

differs from those of the Goose Tickle group is crucial to an interpretation of the trace element behaviour and abundance between the two units.

Davis (1986), in his appraisal of factor analysis, stated that much of the information derived from a factor analysis can simply be obtained by inspection of the correlation matrix. Although the factor analyses here are generally not statistically rigorous, this does not invalidate the interpretations derived from inspection of the correlation matrices. The fact that the factor analysis largely bears out the observations made from the correlation matrices shows that it can be a useful aid to interpretation.

5.2.6.12 Other Trace Element Investigations

Basu et al. (1990) utilised a number of different plots of key trace and rare-earth element parameters to evaluate the behaviour of certain incompatible elements vs. the behaviour of compatible elements, and in addition to evaluate the importance of heavy mineral sorting of fluvial sands of the Amazon basin. The trace element data may be compared using the ternary diagrams Th-Hf-Co (Co representing a strongly compatible element, and Th representing an incompatible element), and La-Th-Sc (with Sc representing a compatible element and La and Th representing incompatible elements). Scandium is a rare earth element (see below), but is a smaller cation, tending to behave differently from other rare earth elemen's and similarly to ferromagnesian cations such as V, Cr, Ni, and Co.

Diagrams showing plots of Th-Hf-Co and La-Th-Sc for the Goose Tickle group and Lower Head Formation are shown on figures 5.10 and 5.11. The average values of

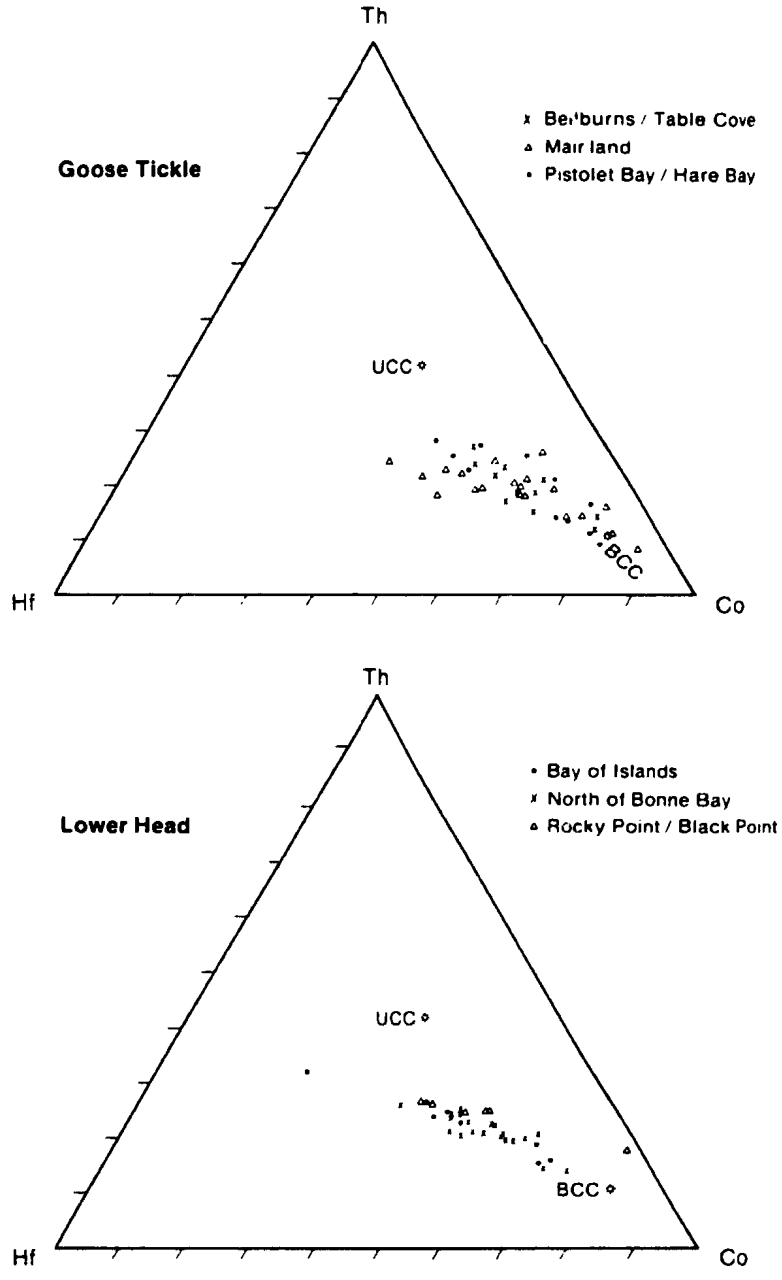


Figure 5.10: Th-Hf-Co diagram for the Goose Tickle group and the Lower Head Formation. UCC=Upper Continental Crust. BCC=Bulk Continental Crust. (values from Taylor and McLennan, 1985).

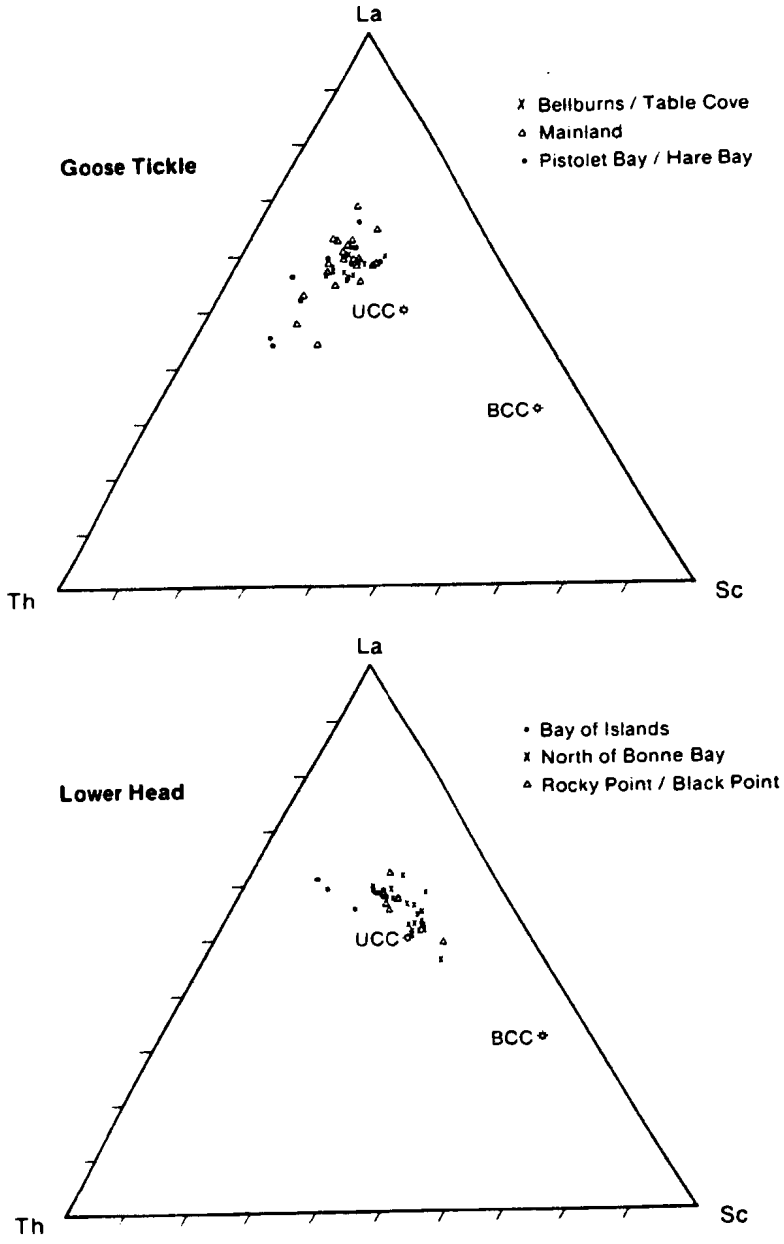


Figure 5.11: La-Th-Sc plot for the Goose Tickle group and the Lower Head Formation. Abbreviations as in figure 5.10.

these parameters for Upper Continental Crust and Bulk Continental Crust are plotted also for comparison (Taylor and McLennan, 1985). Both the Goose Tickle group and the Lower Head Formation show a linear trend towards depletion in Co relative to bulk continental crust, but are relatively enriched in Co relative to upper continental crust, indicating the influence of a mafic source. A number of samples from the Goose Tickle group contain values close to bulk continental crust, probably reflecting their high content of mafic minerals. The linear trend indicates that the relative amounts of Th and Hf vary little and probably represents a trend towards enrichment of Th and Hf by concentration of heavy minerals.

The La-Th-Sc plot appears to show a significant difference between the Lower Head Formation and the Goose Tickle group. The Goose Tickle group shows a relatively narrow range of Sc values, but varies in the relative amounts of Th and La, perhaps reflecting variations in heavy mineral content. The Lower Head Formation shows a conflicting trend towards a relatively constant concentration of Th with variable and higher Sc contents than in the Goose Tickle group. A few samples depleted in Sc probably reflect concentration of heavy minerals.

An inspection of the correlation matrix for the Goose Tickle group shows that Sc is very strongly correlated with V (0.90), and moderately correlated with Co (0.73). It shows only a very weak correlation with Cr (0.39) and a weak correlation with Ni (0.53) and al-alk (0.57).

In the Lower Head Formation Sc shows a slightly weaker correlation with V (0.83) a slightly stronger correlation with Ni (0.60) and a weaker correlation with Co

(0.60). Sc in the Lower Head Formation shows no correlation with Cr (0.17) and al-alk (0.31).

These relationships might suggest that Sc occurs in mafic minerals in the Lower Head Formation, whereas it may have a greater tendency to be associated with clay minerals and to be present as adsorbed ions in the Goose Tickle group. Thus the trend for the Lower Head Formation might reflect an 'unweathered' trend as opposed to a 'weathered trend' for the Goose Tickle group.

Alternatively, the trend for the Lower Head Formation is similar to trends shown by Taylor et al. (1990) as typical of active margin samples, displaying a mixing of upper crust and arc sources. The pattern shown by the Goose Tickle group might then be more indicative of a 'trailing' edge or passive margin signature. This would be consistent with some of the inferences made from major element variation diagrams regarding the passive margin affinities of the Goose Tickle group.

5.2.7 Rare Earth Elements

Rare earth elements (REES) include the lanthanide elements (La to Lu) as well as Y which behaves similarly to the heavy rare earths, and Sc which behaves similarly to other small cations such as V and Cr. McLennan (1989) has noted that REES and Sc have very low solubilities in natural waters and have low residence times in ocean water. This means that they have heterogeneous distributions in seawater and so may be useful for provenance. Bhatia (1985) discussed the significance of rare earth elements for provenance studies, and attempted to discriminate provenance on the basis of several

REE parameters.

McLennan (1989) suggested that discrimination of provenance on the basis of REES is premature since there are not enough data for comparison, much published REE data is incomplete, and the quality of the data is variable. These comments are relevant to this study as the complete suite of REES was not analysed, and in many cases measured values are close to the detection limits, resulting in large errors. This is particularly true of Tb, which is in several cases below detection limits, and other cases is at the detection limit. In addition, the complications of using REES to study provenance include the fact that concentrations of heavy minerals can (and have in the case of the Lower Head Formation and the Goose Tickle group) affect the REE concentration. REE concentrations are particularly high in specific minerals such as monazite and allanite, and zircon shows an enrichment in heavy REES.

The production of chondrite normalised plots (figure 5.12) for these units must therefore be considered semi-quantitative only. Individual plots for both the Goose Tickle group and Lower Head Formation (not shown in figure 5.12) show generally expected patterns with an enrichment of light REES relative to heavy REES. Negative europium anomalies predominate in individual samples, although some samples appear to have smooth patterns.

Taylor et al. (1990) have produced typical chondrite normalised plots for sandstones of varying provenance but like many other authors, they do not include any samples from foreland basins. In terms of overall REE abundance, and light REE enrichment, the sandstones from the Goose Tickle group and Lower Head Formation

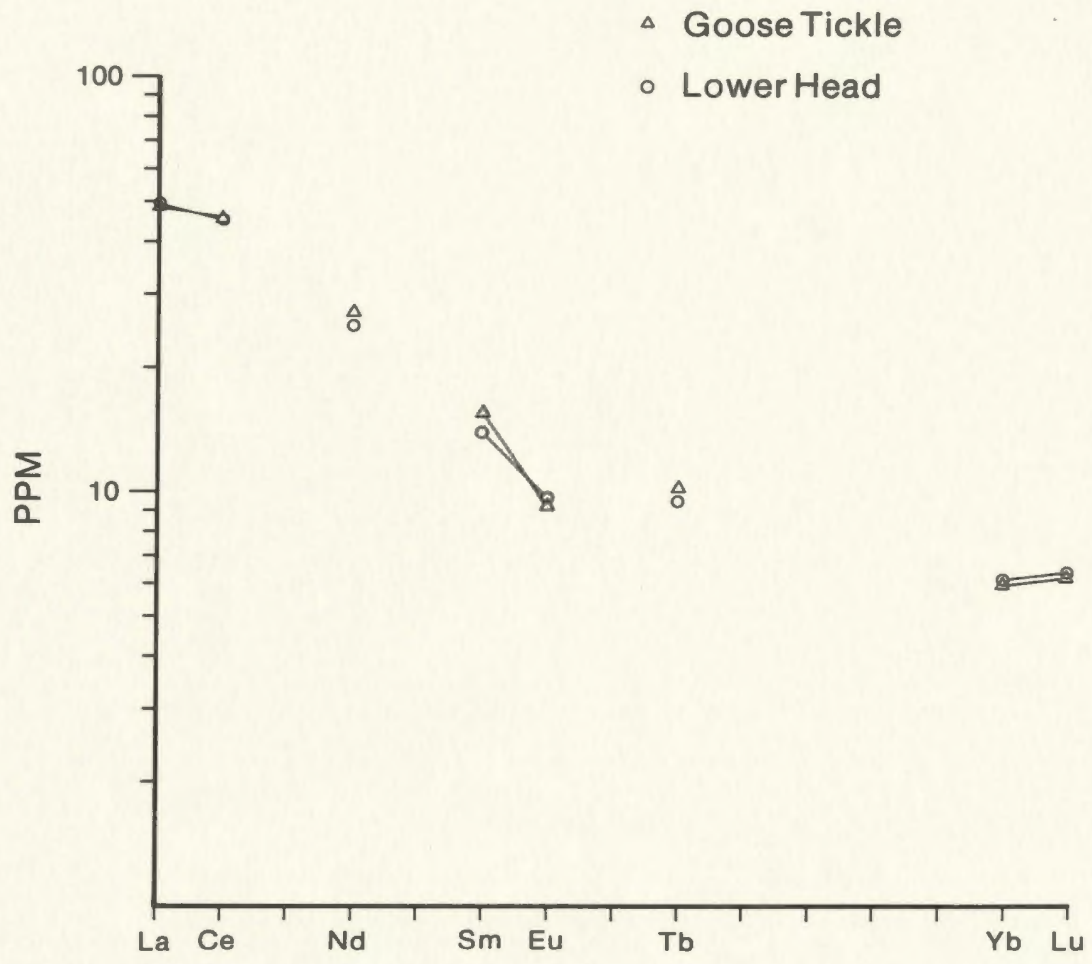


Figure 5.12: Chondrite normalised rare earth element plots for the Goose Tickle group and the Lower Head Formation.

(which are almost identical) display patterns most similar to trailing edge sands of Taylor et al. (1990). It seems that on the relatively local scale of this study, REES may be less useful than major and trace elements in distinguishing subtle provenance variations.

5.3 CONCLUSIONS

5.3.1 Geochemistry of the Goose Tickle group and Lower Head Formation

1. Just as the Lower Head Formation and Goose Tickle group were deemed in chapter 4 to be petrographically distinct, they are also geochemically distinct on the basis of both major and trace element geochemistry.

2. Sandstones of both the Lower Head Formation and the Goose Tickle group display chemical characteristics of both active margin and passive margin sandstones, with a marked signature generated by anomalously high values of Mg, particularly in the American Tickle formation. This is interpreted as the signature of an ultramafic source, which is enhanced by a grain size effect. The passive margin signature is viewed as supporting evidence that recycled sediments may have provided the bulk of the quartzo-feldspathic detritus to these units.

3. High Cr and Ni values appear to define an 'ultramafic factor', but Cr in the Lower Head Formation behaves differently to Cr in the Goose Tickle group. In the Lower Head Formation Cr is correlated with elements which suggest that Cr is present predominantly

in the heavy mineral population. In the Goose Tickle group Cr is more strongly correlated with Ni. The difference in behaviour is here ascribed to more intense weathering of ultramafic material in the source area of the Goose Tickle group providing a greater supply of Cr in the dissolved load. The Cr ions were ultimately adsorbed on clay minerals.

5.3.2 Methodology

1. Interpretation of provenance based on sandstone geochemistry must be carried out with reference to overall sedimentology, including mode of deposition and diagenesis.

2. None of the presently available major element discrimination or variation diagrams seem suitable for analysis of foreland basin sandstones, and in general more study of foreland basin sandstone geochemistry is needed (although it should be noted that Schwab (1986) has provided a summary of available geochemical data for these types of sandstones - see chapter 7).

3. The production of a correlation matrix incorporating both major and trace element parameters can provide useful information, but if many elements are analysed, the process of interpretation may be complex. Correlation matrices can provide information on aspects such as diagenesis and climate as well as provenance. It is preferable to produce a correlation matrix rather than to select key parameters for graphical plots, because the correlation matrix more completely characterises the chemistry of the unit

and may show unexpected, but still informative relationships.

4. R-factor analysis can aid in the interpretation of both major and trace element behaviour, but in certain cases where the number of samples may be too small, or the data is unsuitable for factor analysis, useful interpretations based on inspection of the correlation matrix can still be made.

5. Use of the parameter al-alk in correlation matrices and factor analysis allows the effect of grain size variation to be accounted for. Thus inspection of correlation matrices which include both major and trace element parameters, accompanied where appropriate by factor analysis, is considered a more useful approach to provenance investigations than the use of major element discrimination and variation diagrams.

The conclusions regarding methodology are in keeping with those of Molinaroli et al. (1991). These authors examined various petrographic and geochemical methods for provenance determination (although none of the chemical methods utilised here were investigated). Using discriminant function analysis Molinaroli et al. (1991) discovered that none of the models they tested could classify with complete success the data which were used in the original construction of the models. Molinaroli et al. (1991) suggested that deterministic models of provenance interpretation are not successful, and that actualistic models of provenance interpretation constructed on a case by case basis may be more appropriate. The reliability of provenance interpretation, they suggested, must

be improved by utilising a combination of different methods of investigation, as well as statistical analysis of the data. Based on the investigations of geochemical methodology in this chapter, the author concurs with these statements.

The type of geochemical investigation used in this study, viz. the combination of analysis of correlation matrices and factor analysis of major and trace element parameters is, to the author's knowledge a new variation on the study of geochemical data in sandstones, and clearly has potential in actualistic studies of the type envisioned by Molinaroli et al. (1991).

CHAPTER 6

PROVENANCE

6.1 INTRODUCTION

Information from chapters 2 and 3 has suggested that sandstones of the Goose Tickle group and Lower Head Formation may not be entirely derived from the Humber Arm and Hare Bay Allochthons. Although an intrabasinal source for black and green shale fragments has been clearly identified, the general petrographic and geochemical characteristics of the two units suggest that multiple sources, most of them extrabasinal, have contributed. The overall petrographic uniformity of the units suggests that mixing of the extrabasinal sources has taken place prior to deposition. The information derived from field studies is not, however, adequate to determine whether the sandstones in either unit were derived wholly from sources whose equivalents are now preserved in western Newfoundland, or whether mixing of sediment from exotic and local sources took place prior to transport into the foredeep and trench slope basins.

It is now appropriate to try to identify the possible source terranes for the grain types which have been identified in chapter 4. Cambrian sandstones are of particular interest as possible sources of recycled siliciclastic detritus. Because of the diverse nature of the detritus in the Goose Tickle group and Lower Head Formation, information from other miscellaneous sandstone units may also have a bearing on provenance.

Methods for data collection from Cambrian and miscellaneous sandstone units

were similar to those outlined in chapters 4 and 5. Petrographic data for these units are provided in appendix 4, sections A4.4 and A4.5. Geochemical data are provided in appendix 5, sections A5.7 through A5.10.

Several possible source terranes for detritus in the Lower Head Formation and Goose Tickle group have been suggested by other authors (see chapter 1) or are possibilities. They are:

1. Peripheral bulge or related feature;
2. Humber Arm and Hare Bay allochthons;
3. Grenville basement;
4. Fleur de Lys Supergroup;
5. Dunnage or similar island arc terrane.

6.2 PERIPHERAL BULGE AND OTHER BASIN MARGIN FEATURES

6.2.1 Peripheral Bulge

Jacobi (1981) proposed a tectonic model for western Newfoundland which explained the widespread unconformity in Early and Middle Ordovician Appalachian carbonate units as being a result of upwarp on a peripheral bulge along the western side of the foredeep basin. He further stated that the paleocontinental margin 'drifted east over a peripheral bulge and on into the trench'. This implies that the peripheral bulge is a permanent feature of a foreland basin while it is undergoing loading and flexure (see also Quinlan and Beaumont, 1984). Thus the bulge, which was certainly present during the Arenig at the time of deposition of the Lower Head Formation (e.g. Knight et al.,

1991), was also a presumably a feature of the basin during deposition of the Goose Tickle group.

Exposure of the peripheral bulge would have generated a supply of detritus from the western margin of the basin. This detritus would have been derived from platformal sediments which now constitute the major part of the parautochthonous sequence. The uppermost examples include the shallow water carbonates of the Port au Port Group, the St. George Group and the Table Head Group, none of which are likely to have been major sources for quartzo-feldspathic siliciclastics.

6.2.2 Faults Along the Western Margin of the Basin

Some considerable portion of basin subsidence could have been accommodated along faults on either side of the foredeep basin (e.g. Bradley, 1989). It has been suggested (Waldron and Stockmal, 1991) that these might include reactivated rift faults. It has been shown by Stenzel et al. (1990) and Stenzel (1992) that the Cape Cormorant Formation, which directly underlies the Mainland formation, was derived from a fault scarp which unroofed a considerable section of the carbonate platform along the western margin of the basin. Minor calcarenite beds interbedded with the sandstones of the Mainland formation suggest a periodic supply from a similar source, but comparable lithologies are not present in the American Tickle formation. Minor calcarenites in the Lower Head Formation may also have been derived from the faulted western margins of the trench slope basins.

Again, there is no evidence to suggest that these faults exposed a significant

amount of siliciclastic material.

6.2.3 Faults Along the Eastern Margin of the Basin

On the eastern margin of the foredeep basin, conglomerates and calcarenites of the Daniel's Harbour Member are interpreted to have been derived from unroofing of the floor of the foreland basin and the upper part of the carbonate platform along faults which may have been generated in the early stages of emplacement of the Humber Arm and Hare Bay allochthons (Stenzel et al., 1990).

Although this mechanism may supply detritus to the foredeep basin, the Daniel's Harbour Member is dominated by carbonate detritus, and is unlikely to be closely related to sources of siliciclastic detritus in the Goose Tickle group. Faults which generated the Howe Harbour member (see chapters 2 and 3) clearly exposed lithologies which were unrelated to the basin margin and provided extrabasinal detritus, and these faults are best considered as compressional features within the source area, rather than a basin margin feature.

Faulting also took place along the eastern margin of the trench slope basin (or basins) in which the Lower Head Formation was deposited. These unroofed sediments locally provided a variety of sedimentary detritus derived from sediments similar to the Cow Head Group (see chapter 3), but Cow Head type detritus is not otherwise widespread in the Lower Head Formation.

6.2.4 Older Parautochthonous Sandstones

Potential sources of siliciclastic sediment in the parautochthon lie below the platform carbonates, and are related to rifting and the early phases of development of the passive margin. They include the Bradore, Bateau and Hawke's Bay Formations, along with the volcanic Lighthouse Cove Formation. The bulk of the siliciclastic detritus in the parautochthonous sequence was probably derived from Grenville basement. None of the sediment supply routes described above appear likely to have penetrated on a regional scale through the carbonate platform to the underlying siliciclastics, and thus parautochthonous siliciclastic units are unlikely to have been exposed to provide extensive detritus to the Lower Head Formation and Goose Tickle group. In addition, the interpretation of the Lower Head Formation as a trench slope basin located on the east side of the foredeep basin (see chapter 3) makes it unlikely that sediment from the western margin could have penetrated into its area of deposition.

An investigation into the makeup of Cambrian parautochthonous siliciclastics is, however, relevant, as related rocks may have provided detritus which was subsequently recycled into the Lower Head Formation and Goose Tickle group. The main parautochthonous Cambrian sandstone units are briefly described below.

6.2.4.1 Bradore Formation

The Bradore Formation is a Cambrian unit which unconformably overlies Grenvillian crystalline basement (Williams and Stevens, 1969; Hiscott et al., 1984). It consists of coarse conglomerates, pink subarkosic sandstones, and white quartzites

(Williams and Stevens, 1969; Waring, 1975; Hiscott et al., 1984). The lower part of the unit has been interpreted as having been deposited by braided streams (Hiscott et al., 1984) and the upper part is of shallow marine origin. On the island of Belle Isle, off the northern tip of the Northern Peninsula, the Bradore Formation unconformably overlies mafic volcanics of the Lighthouse Cove Formation (Williams and Stevens, 1969). These volcanics are continuous with mafic dykes which intrude the crystalline basement and are generally interpreted as having been formed during the rifting process.

Williams and Stevens (1969) described the framework constituents of the Bradore Formation as quartz and feldspar, with local magnetite and minor metamorphic rock fragments. They reported the presence of purplish amygdaloidal basaltic rock fragments in places but described these occurrences as being restricted to certain horizons. The author was able to study conglomeratic and pebbly sandstones from the Bradore Formation collected by N.P. James and also collected some pink pebbly sandstone with abundant skolithos burrows from a locality near Hawke's Bay. No samples were point counted.

The grains are well rounded, and are cemented by quartz overgrowths. Quartz and potassium feldspars (both microcline and orthoclase) predominate. The chemistry of the Bradore shows very low levels of trace elements reflecting the dilution effect of abundant silica in the unit. In fact, the loading on silica is so high that the analyses do not plot on the discrimination diagram of Roser and Korsch (1988) (figure 6.1). This is not surprising, since the diagrams of Roser and Korsch (1988) are essentially designed for turbidites. Otherwise the Bradore clearly displays the signature of having been

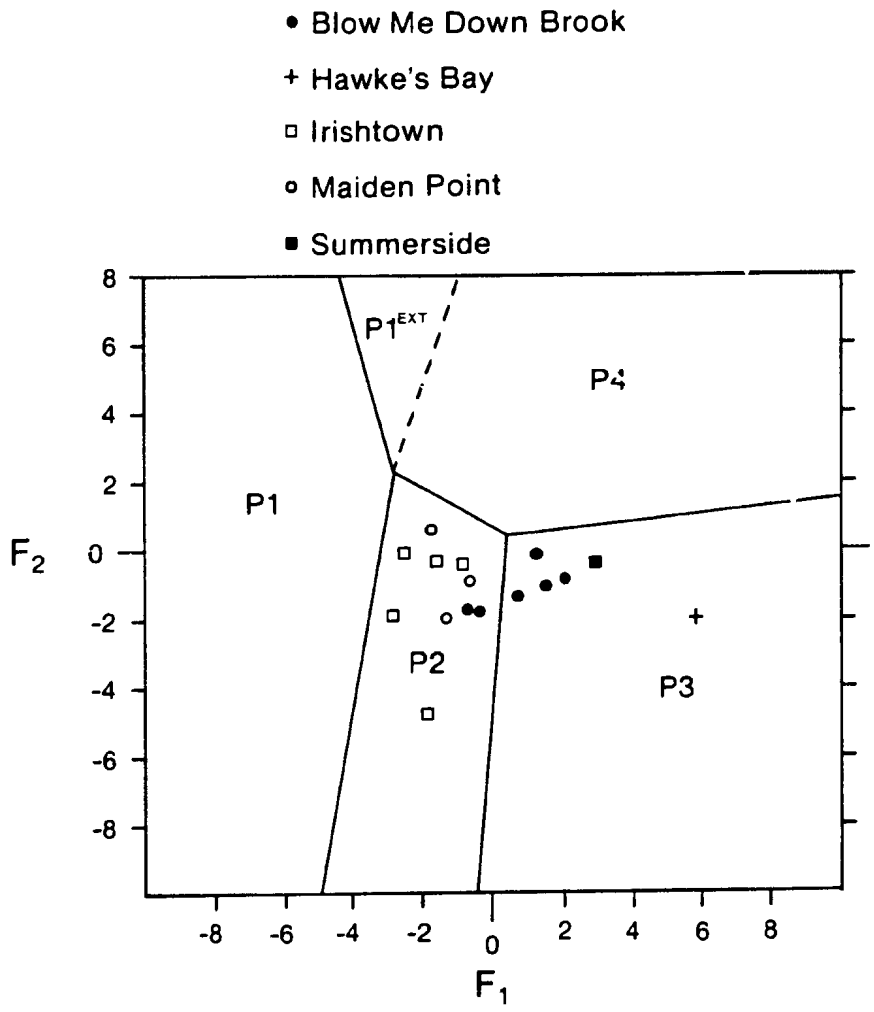


Figure 6.1: Discriminant plot of major element parameters for Cambrian sandstones. Fields from Roser and Korsch (1988). P1 = mainly mafic source. P2 = mainly intermediate source. P3 = mainly felsic source. P4 = mainly recycled source.

deposited on a passive margin (figure 6.2).

On Belle Isle, there is another unit of conglomerates and quartzose sandstones known as the Bateau Formation (Williams and Stevens, 1969). The Bateau Formation is similar to the Bradore Formation in some respects but is cut by dykes related to the Lighthouse Cove Formation. Belle Isle is the only locality where this relationship is displayed, however Tuke (1966, 1968) noted the existence of quartzose sandstones off the northeast coast of the Northern Peninsula which he equated with the Bradore Formation, but which Williams and Stevens (1969) equated with the Bateau Formation. Detailed petrographic information is not available for the Bateau Formation, but field descriptions suggest that it is similar to the Bradore and Hawke's Bay (see below) formations.

6.2.4.2 Hawke's Bay Formation

The Hawke's Bay Formation is a Cambrian unit of variously coloured quartzose sandstones with minor shales. The unit has been interpreted as shallow marine in origin (Knight, 1983).

Sandstones of the Hawke's Bay Formation are moderately to poorly sorted and the grains are rounded to subangular. Silica cement is ubiquitous and consists of very well developed amalgamated quartz overgrowths. Variable amounts of opaque oxide cement were also observed. A small amount of clay matrix is present in areas of the sample where there are no quartz overgrowths. Quartz grains are well rounded and show slightly undulose extinction. A small proportion of the grains show multiple vacuoles

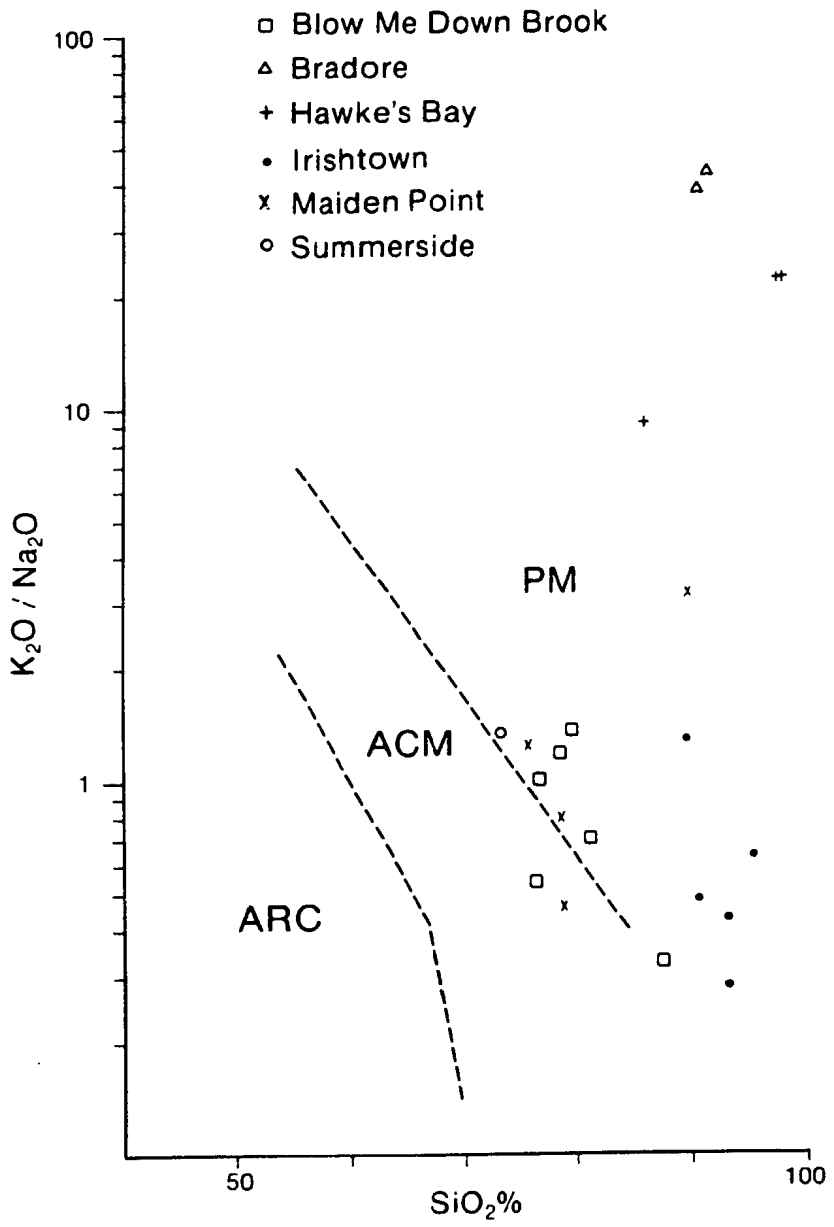


Figure 6.2: Plot of K_2O vs. Na_2O vs. SiO_2 for Cambrian sandstones. Fields after Roser and Korsch (1986). ARC=arc. ACM=Active margin. PM=Passive margin.

and contain mineral inclusions. Feldspars include both potassium feldspar and plagioclase feldspar. Potassium feldspars (Plate 6.1) are euhedral, cloudy and may contain rounded cores of clearer feldspar, or of plagioclase feldspar. They luminesce bright blue under cathode luminescence, which is somewhat at odds with their apparently authigenic origin (see e.g. Kastner, 1971).

Zircon, muscovite, and tourmaline have been identified as accessory minerals. Glauconite is present in a section along the south shore of the Port au Port Peninsula (appendix 1, location map 1). The grains are rounded, cryptocrystalline, and are associated with small opaque iron oxide particles which have grown both within the glauconite grains and surrounding them. Chemically, the Hawke's Bay Formation is silica rich and shows chemical characteristics of having been deposited in a passive margin (figures 6.1 and 6.2). A notable feature of the chemistry of both the Hawke's Bay and the Bradore formations is the extraordinarily high concentration of Co which is enigmatic but may be associated with opaque cementing materials in both units.

6.3 THE HUMBER ARM AND HARE BAY ALLOCHTHONS - POTENTIAL SOURCES OF RECYCLED SEDIMENT

Cambrian siliciclastic units in the Hare Bay and Humber Arm allochthons are important to consider when investigating the provenance of the Goose Tickle group and Lower Head Formation, as similar units may have been located in a position where they could have provided detritus to younger Ordovician sandstones. These allochthonous Cambrian units are interpreted as deeper water slope/rise equivalents of the Cambrian

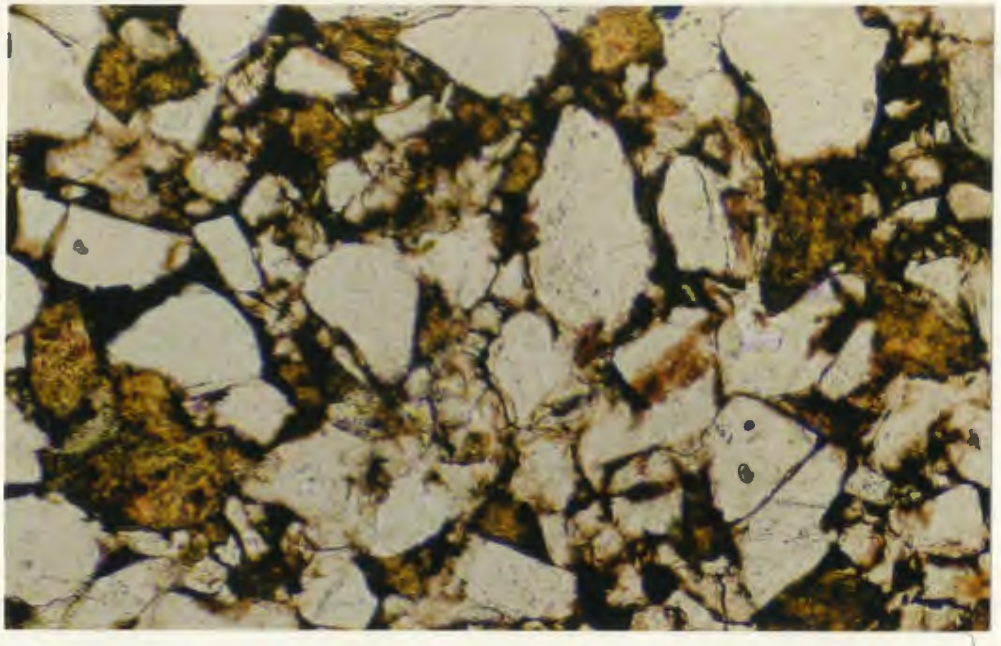


Plate 6.1: General appearance of Hawke's Bay sandstone cemented by opaque material. Yellow grains are potassium feldspar. Plane Polarised Light. X32.

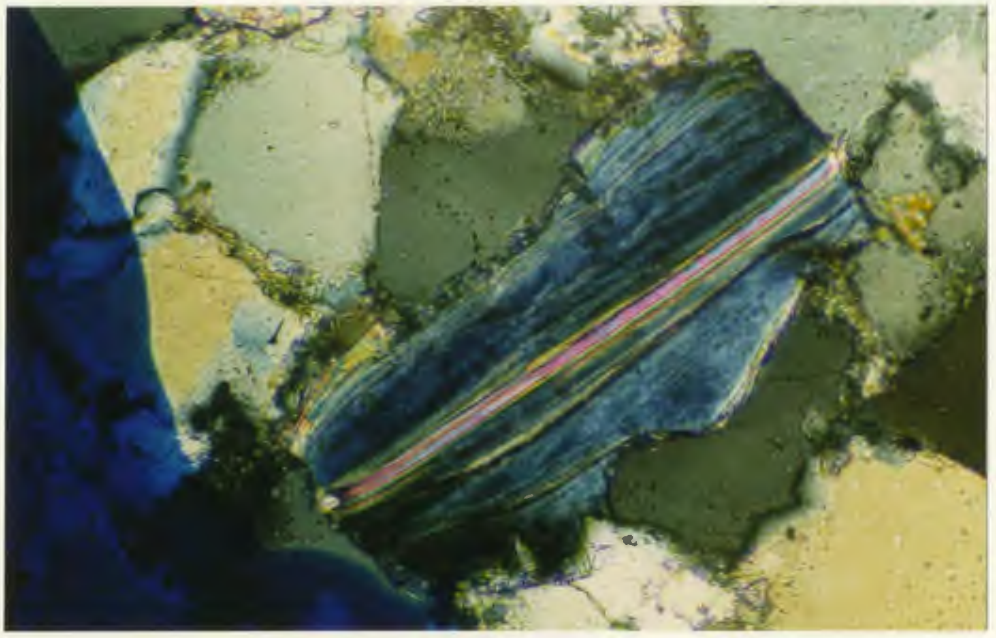


Plate 6.2: Distinctive chlorite grains in the Irishtown Formation. Blue line was used to locate the grain. Plane polarised light. X310.

parautochthonous siliciclastics. They are generally considered to have a westerly provenance and the siliciclastic material is probably derived from Grenville basement (Stevens, 1970).

6.3.1 Blow me Down Brook, Summerside, and Maiden Point Formations

The Blow me Down Brook and Summerside formations are two units of predominantly coarse-grained thick-bedded sandstones with lesser proportions of red and green slates, and minor dark grey slates. The sandstones are dominated by the A division of the Bouma sequence and are interpreted as having been deposited by high concentration turbidity currents (e.g. Lindholm and Casey, 1989). The Summerside Formation was previously thought to be the lowermost formation of the Curling Group (Stevens, 1965; Botsford, 1988) and may be late Precambrian or Early Cambrian in age.

The Blow me Down Brook Formation was once thought to be an Ordovician equivalent to what is now known as the Lower Head Formation, but it was later interpreted as being late Precambrian or Early Cambrian in age (Quinn, 1985, 1986; Waldron, 1985; Lindholm and Casey, 1989, 1990) isolated as the highest thrust slice within the sedimentary package of the Humber Arm Allochthon (e.g. Quinn, 1985; Cawood and Botsford, 1991).

As part of this study the author collected acritarch samples from the Blow me Down Brook Formation at its type section. These samples were processed and specimens identified by P. Cashman of the University of Saskatchewan. He determined the age as Early Middle Cambrian, which is rather younger than the age inferred by Lindholm and

Casey (1990). The Blow me Down Brook Formation may be an equivalent of the Summerside Formation, or, as suggested by Quinn (1985), may be older. Both the Blow me Down Brook and Summerside Formations have been interpreted as slope/rise deposits related to rifting and the early development of the continental margin, but this is controversial (Williams and Hiscott, 1987; Lindholm and Casey, 1989).

In the Bonne Bay area, Quinn (1985), mapped an equivalent to the Blow me Down Brook Formation which she informally named the Sellars formation. Quinn (1985) carried out a petrographic analysis of the Sellars formation in the Bonne Bay area. The results of this analysis are shown in figure 6.3 for comparison with results from Cambrian sandstones examined for this study (figure 6.4). Note that Quinn (1985) did not use the Gazzi-Dickinson method in her study, but the datasets are still generally comparable (see discussion in Quinn, 1985).

The sandstones of the Blow me Down Brook Formation are poorly to very poorly sorted with a high variability in grain size, ranging from matrix to pebble size. Framework grains are sub-angular to rounded. They are generally equant and show no obvious preferred orientation. The matrix content is very high, and matrix minerals consist of chlorite/sericite with some illite identified in the SEM. Pink plagioclase feldspars are very distinctive in some beds of the Blow me Down Brook Formation, but are not present in others. Generally speaking, the unit is lithic poor, and feldspars are almost exclusively plagioclase. Schwab (1991) has also carried out some analyses on the Blow me Down Brook Formation which are in general agreement with those of the author.

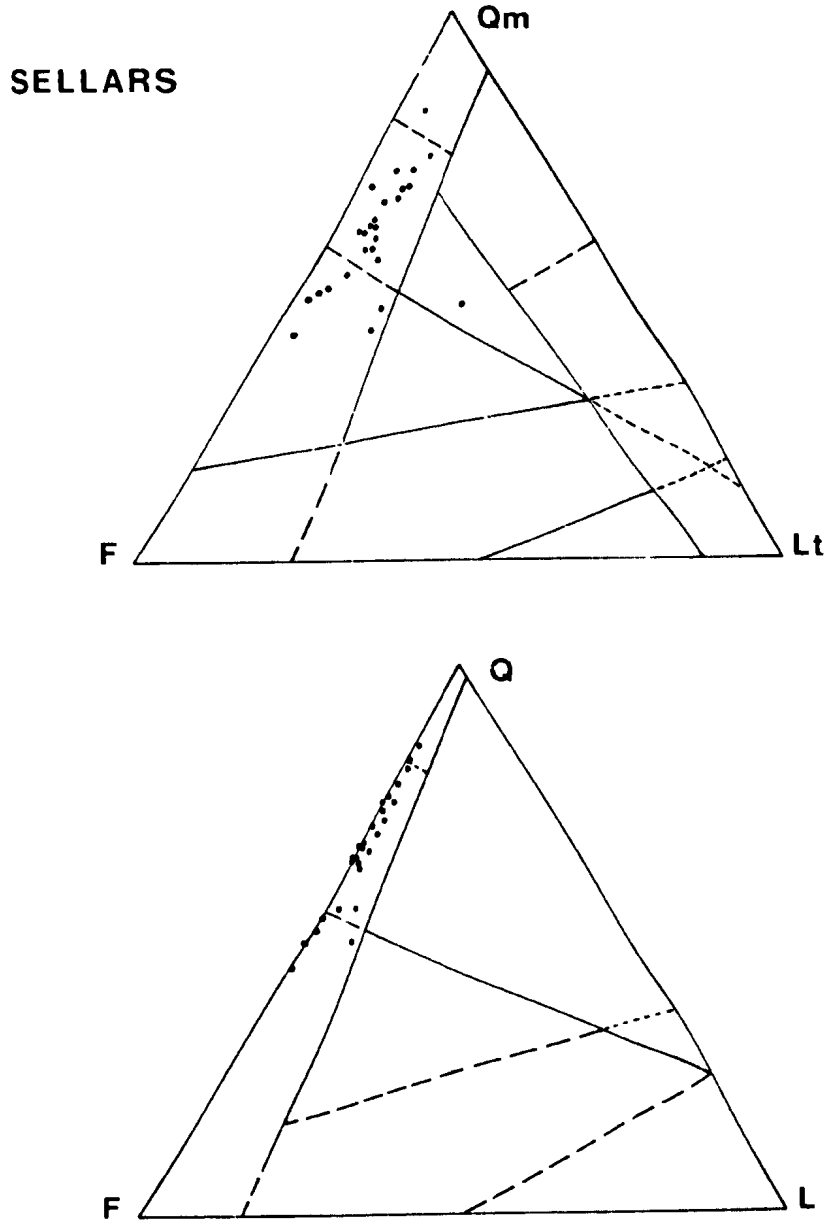


Figure 6.3: QFL and QmFLt plots for Sellars formation (Blow me Down Brook equivalent), from Quinn (1985). Fields from Dickinson et al. (1983) (see chapter 4).

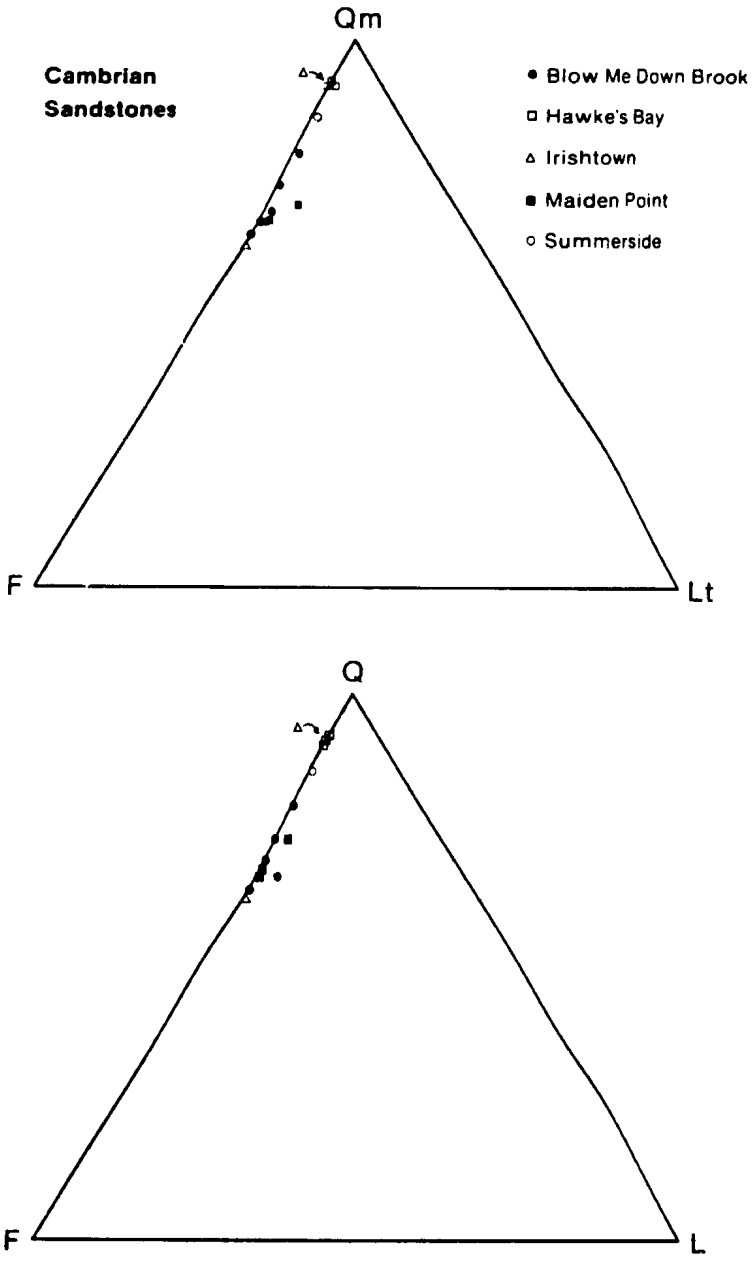


Figure 6.4: QmFLt and QFL plot for Cambrian sandstones, data from this study.

Quartz grains in the Blow me Down Brook Formation generally show undulose extinction and are free of mineral inclusions, but commonly contain trails of vacuoles. They display variable rounding, with some of the well-rounded grains showing a distinct blue luminescence. Minor polycrystalline quartz containing only a few subgrains is also present. Subgrains may be sutured or simple and vary in size within a single grain.

Untwinned plagioclase feldspars are cloudy and generally larger than the mean grain size. Clear grains of plagioclase showing albite twinning tend to be smaller than the mean grain size. Microcline is present in small amounts at the type section in the Bay of Islands (appendix 1, location map 2) and many pink plagioclase feldspars show evidence that they are altered microcline, as relict cross-hatch twinning is visible. Untwinned potassium feldspar is also present, as is antiperthite containing stringy blebs of bright blue luminescing potassium feldspar in dominantly non-luminescing albite grains.

Probe analyses of some feldspars in the Blow me Down Brook Formation are shown in figure 6.5, indicating that the feldspars are dominated by pure to nearly pure albite, suggesting that original feldspars have been altered and replaced by authigenic albite. This is supported by the fact that feldspars in the Blow me Down Brook are generally non-luminescing.

Shale chips, probably of intraformational origin, are present in some samples. The most common rock fragments are graphic quartz-feldspar intergrowths. Minor metamorphic quartz-feldspar and feldspar aggregates are also present. Rare murky silica fragments may be derived from a felsic volcanic source. Glauconite is prominent in

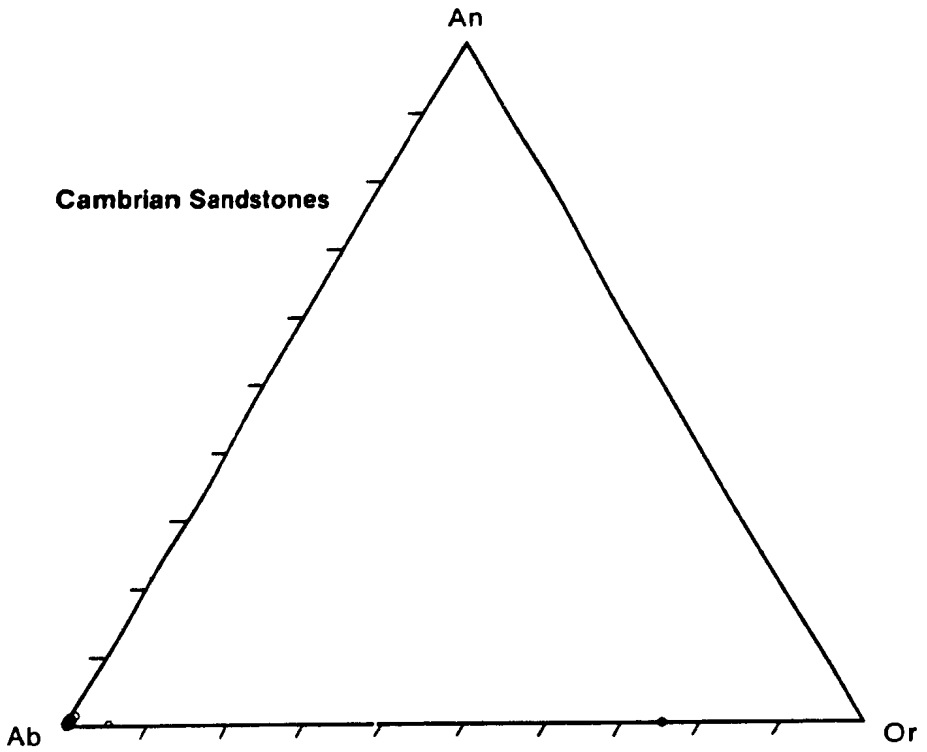


Figure 6.5 AnOrAb plot for feldspars from the Blow me Down Brook Formation.

samples from the coastal area north of the Port au Port Peninsula, and it is worth noting that the Hawke's Bay Formation and the Mainland Formation in that area also contain prominent, although not abundant, glauconite suggesting a relationship between all three units. Other accessory minerals include biotite, muscovite, chlorite, zircon, garnet, tourmaline, monazite, and opaque minerals.

Sandstones of the Summerside Formation are similar in all respects to those of the Blow me Down Brook Formation except that they are more altered.

The Maiden Point Formation occurs in the Hare Bay Allochthon and is a ?late Proterozoic or Early Cambrian equivalent of the Blow me Down Brook Formation. It occupies the same high structural position in the Hare Bay Allochthon as does the Blow me Down Brook Formation in the Humber Arm Allochthon. In the field its appearance is similar to the Blow me Down Brook and Summerside Formations, except that it has been more strongly metamorphosed and is more indurated. The Maiden Point Formation was described by Tuke (1966) and Smyth (1973).

Tuke (1966) described the Maiden Point Formation as containing quartz, plagioclase, mica, iron ore, and rock fragments. Tuke (1966) suggested, on the basis of a bimodal grain size distribution, that quartz was derived from two different sources, an igneous and a metamorphic source. He determined that the matrix in most Maiden Point sandstones was very abundant (average 40%) and composed of quartz and clinochlore. He did not detect any potassium feldspar, and concluded that the grains were probably angular prior to diagenesis. He noted the heavy minerals tourmaline, zircon, and rutile. The rock fragments were described as significantly altered, consisting

of coarse acidic igneous rock, feldspar porphyry, fine grained acid volcanics, metaquartzite, orthoquartzite, altered glass, and in one thin section, oolites. This is rather a diverse array of rock fragments in comparison to those observed by the author, and actually resembles the American Tickle suite of rock fragments. The two units can appear similar in the field and it is possible that Tuke (1966) was mistaken, or that the Maiden Point Formation may consist of more than one petrofacies. The small number of samples investigated by the author (figure 6.4) do not show such a variety of rock fragments, and the Maiden Point Formation, as observed in this study, contains predominantly quartz, plagioclase feldspar and sericite matrix.

All of the Maiden Point, Blow me Down Brook and Summerside formations show chemical characteristics of passive margin deposition but plot very close to the boundary of the active margin field in the diagram of Roser and Korsch (1986) (see figure 6.2). In fact, they plot very close to the Goose Tickle group and Lower Head Formation on this diagram (see chapter 5) which might be considered anomalous in view of their supposed derivation from a cratonic source. Roser and Korsch (1986) noted a similar unusual chemistry in some Quebec equivalents of the Maiden Point, Summerside, and Blow me Down Brook formations, and ascribed this to the contribution of a volcanic source. Clearly, volcanic detritus is not abundant in these units, but weathering of volcanic rocks in the source area may have left a signature on the chemistry of the clay minerals in the matrix.

All of these units are clearly chemically fairly similar as can be seen by examination of figures 6.1 and 6.2. The diagram of Roser and Korsch (1988) (figure

6.1) is certainly successful in discriminating these Cambrian sandstones from the chemically distinctive Lower Head Formation and Goose Tickle group. Interestingly, the Cambrian sandstones plot in the P3 and P2 fields, which is again suggestive of a volcanic source not apparent from their petrographic characteristics.

The chemical similarity among the above units is not the only significant feature of the Maiden Point, Blow me Down Brook and Summerside Formations. The quartz population is similar in style to that of the Lower Head Formation and Goose Tickle group, with the dominance of monocrystalline quartz, the variable rounding and the abundance of vacuoles. The abundant untwinned plagioclase in the Cambrian units could easily account much of the untwinned plagioclase and altered albite in the Ordovician units. The high proportion of matrix suggests that these sediments would have provided single grains rather than sedimentary rock fragments as detritus. The lack of cementation would have resulted in grains with very few abraded quartz overgrowths, and indeed there are very few abraded overgrowths or sandstone fragments in the Goose Tickle group and Lower Head Formation.

The fact that the Blow me Down Brook and Maiden Point formations constitute the highest sedimentary slices in their respective allochthons may also be significant. This is because as high slices their equivalents are most likely to have been exposed during emplacement of the sedimentary slices of the allochthon. It is clear that the lower sedimentary slices of the allochthons were emplaced at least partly by submarine gravity flow processes, but the higher slices show evidence of harder thrusting (e.g. Tuke, 1966; Williams and Smyth, 1983) and compressional forces may have been sufficient to uplift

them above sea level.

6.3.2 Irishtown Formation

The Irishtown Formation is a unit of early Middle Cambrian age which is younger than the Summerside Formation and is exposed in the Humber Arm Allochthon in the Bay of Islands area (appendix 1, location map 2). The unit consists of quartzite beds of varying thickness, interbedded with dark grey shales. At several localities in the Bay of Islands area and one locality in the Bonne Bay area, there are thick cobble - boulder conglomerates with a quartzite matrix.

The unit has been interpreted as the result of deposition by turbidites, and the conglomerates in the Bay of Islands area have been interpreted as having been deposited in a submarine canyon (N.P. James, pers. comm., 1985). The unit was informally termed the Barters formation in the Bonne Bay area by Quinn (1985) whose petrographic analysis (again samples were not counted using the Gazzi-Dickinson method) is reproduced in figure 6.6 for comparison with results from this study (shown in figure 6.4).

Sandstones of the Irishtown Formation are moderately sorted. The framework grains are subangular to rounded. Most are equant and show no preferred orientation. However, some micas are elliptical and aligned with their long axes parallel to bedding. Samples contain varying amounts of matrix and quartz cement with minor opaque cement. Quartz overgrowths coalesce to form the cement in most cases, with later (at least two) generations of calcite and dolomite cement being common. Matrix, where

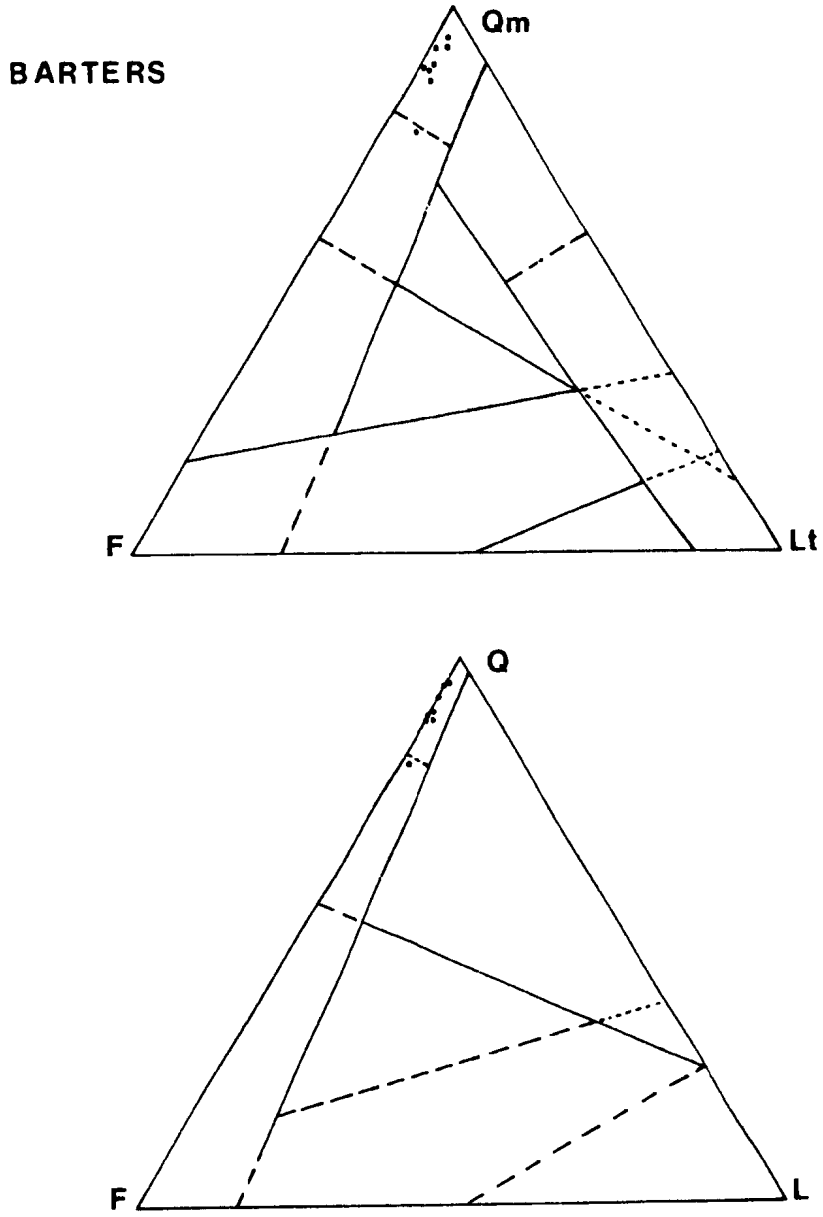


Figure 6.6: QFL and QmFLt plots for Barters formation (Irishtown equivalents), from Quinn (1985). Fields as for figure 6.3.

present, is chloritic/sericitic and framework grains are commonly matrix supported. Feldspars are locally partially or completely replaced by calcite and are commonly partly sericitised.

Although the unit is texturally dissimilar to the Blow me Down Brook, Summerside and Maiden Point formations, the grain types are similar. Again albite, predominantly untwinned, is the dominant feldspar. Some antiperthite is present and intraformational shale chips are ubiquitous. In the conglomerates, a wider suite of clasts is present including granite, grey-green gneiss, bioclastic limestone, fine grained limestone, quartz feldspar intergrowths, Bradore-type sandstone, and oncolitic limestones similar to those in the Forteau Formation, a part of the Labrador group (N.P. James, unpublished material). All of these fragments indicate derivation from older platformal sediments similar to those now exposed in the parautochthonous sequence, and from Grenville basement.

The most distinctive feature of the Irishtown Formation is a grain type which consists of chloritised biotites interlayered with muscovite. These grains show strong berlin blue interference colours (Plate 6.2). A plot of electron probe data for the chlorites is shown in figure 6.7 and it indicates that they are metamorphic chlorites derived from pelites. This suggests a low grade metamorphic source in part for the Irishtown. Although occasional examples of these distinctive grains are seen in the Blow me Down Brook and Maiden Point formations, they are ubiquitous in the Irishtown.

For several reasons, Irishtown Formation equivalents are considered less likely to have been major sources for the bulk of the siliciclastic material in the Goose Tickle

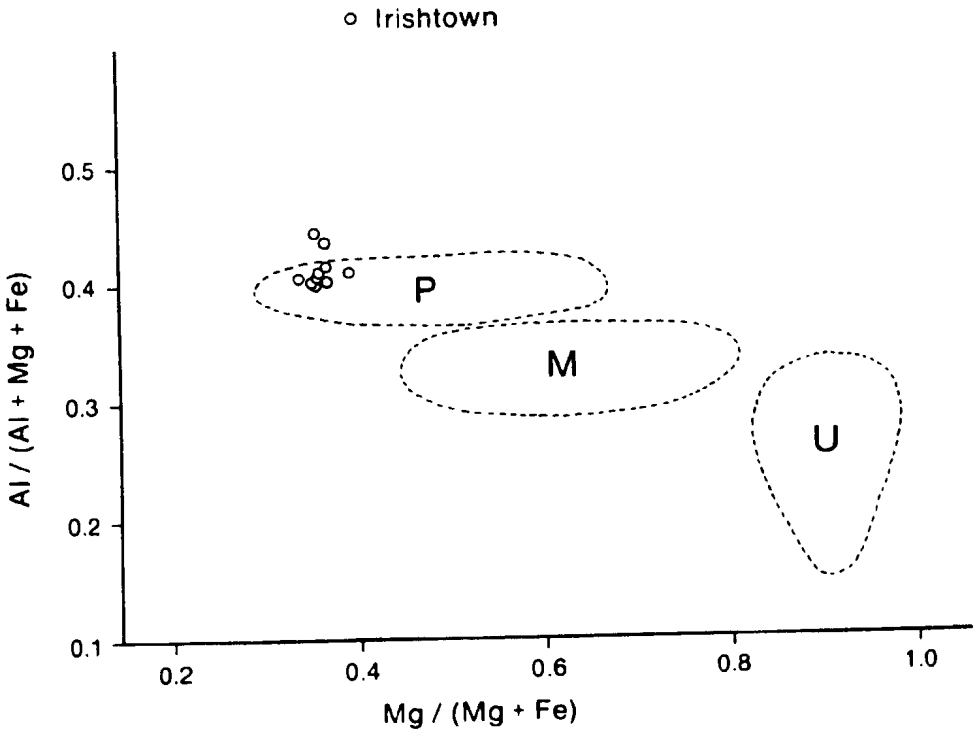


Figure 6.7: Plot of Al/(Al+Mg+Fe) vs. Mg/(Mg+Fe) for Irishtown chlorites. Data plot close to field for pelitic chlorites (P) of Laird (1988).

group and Lower Head Formation. Firstly, the greater induration and early silica cementation of the Irishtown in comparison with the Maiden Point and Blow me Down Brook Formations would likely have provided sedimentary rock fragments rather than loose grains, and the Goose Tickle group and Lower Head Formation do not contain many of the distinctive pelitic chlorite grains (although a very few have been observed). Secondly, the Irishtown, as part of the structurally lowest sedimentary package within the Humber Arm Allochthon, may not have been in as favourable a structural position to supply detritus.

6.3.3 Provenance of Allochthonous Passive Margin Siliciclastic Units

Although the provenance of the Cambrian sandstones is generally considered to be westerly and from the Grenville basement, some authors have studied shales of allochthonous units and noted more subtle variations in provenance.

Evidence of a change in provenance of passive margin sediments through time is provided by Botsford (1988) who noted an increase in chlorite abundance at the base of the Cooks Brook Formation (Late Middle Cambrian). At the base of the Middle Arm Point Formation (Tremadoc) he noted another change in provenance with shales of this unit apparently showing geochemical affinities to the early Middle Cambrian Irishtown Formation.

Sucheki et al. (1977) investigated the clay mineralogy of the Cow Head Group (which is equivalent to the Cooks Brook and Middle Arm Point formations) and noted three distinct clay mineral suites. They identified a late Middle Cambrian to early Lower

Ordovician illite-chlorite suite, a Lower Ordovician illite-expandable chlorite suite, and a late Lower to Middle Ordovician corrensite-illite-smectite suite.

The early change to material richer in chlorite was probably not related to detritus supplied by an ophiolite. Since a carbonate bank was present to the west, the chlorite may have ultimately been derived from island arc volcanics which were present in Iapetus as early as the Middle Cambrian (Fyffe and Swinden, 1991). Sucheki et al. (1977) suggested that corrensite was the product of diagenetically altered magnesium-rich volcanogenic detritus, and the late Lower Ordovician appearance of corrensite may be the first indication of input by ophiolitic material.

The change in provenance at the base of the Middle Arm Point Formation to shales which show geochemical relationships to the Irishtown Formation is interesting. It may be the first indicator of offshore equivalents of the Irishtown Formation being uplifted to provide the initial phases of detritus which was later provided by units similar to the Maiden Point and Blow me Down Brook Formations. The possibility of a contribution by Irishtown equivalents also raises the spectre of another source for Cr, since the Irishtown shales are unusually rich in Cr, a feature which was not explained by Botsford (1988). Irishtown sandstones do not display similarly elevated values of Cr.

6.3.4 Discussion

Several problems arise when trying to evaluate the importance of Cambrian allochthonous siliciclastic units as potential sources of detritus for Ordovician foredeep and trench slope basin sandstones:

1. From the above review, it can be seen that there is little information on the petrographic makeup of Cambrian siliciclastics, and the chemical information provided here combined with previous work on shales, suggests that the provenance of Cambrian siliciclastic units may not be as well understood as has been thought. This clearly has an effect when evaluating their significance as possible sources;

2. Albitisation of feldspars in these Cambrian sandstones is ubiquitous, and is also problematic (see e.g. Ogunyomi et al., 1980; Quinn, 1985). A complete understanding of the significance of these feldspars as detrital grains is precluded by a lack of knowledge as to how and when they were altered;

3. Allochthonous Cambrian sandstones do not closely resemble their parautochthonous equivalents in terms of detrital makeup. Some of these differences clearly relate to differing depositional environments, but again the controversy as to the exact age and depositional environment of the allochthonous Cambrian units must hinder an understanding of them as sources of detritus;

4. Two types of grains which are clearly resedimented are found in the Goose Tickle group and Lower Head Formation but not in the allochthonous Cambrian sandstones. Microcline grains which are generally more rounded than the rest of the quartz and feldspar population are abundant. There are also a very few silica cemented sandstone fragments containing rounded grains of quartz, microcline and plagioclase. Although microcline is present in the Cambrian units, it is not abundant, is frequently wholly or partly replaced by albite, and is not as well rounded as that found in the Ordovician sandstones. The microcline in the Goose Tickle group and Lower Head Formation most

resembles grains found in the Bradore Formation. However, when microcline is found in the quartz cemented sedimentary rock fragments it is associated with plagioclase, which is not common in the Bradore Formation.

Although it was earlier asserted that no direct evidence of exposure of lower siliciclastic platformal sediments exists, it is not impossible to envisage a scenario in which units like the Bradore could have been exposed in the source area. Grenville basement has certainly become involved in thrusting during later phases of orogenesis (Grenier, 1990), and it is possible that cover units equivalent to the Bradore could have been exposed during early phases of basement uplift. Also relevant to this discussion are the grains of shallow water carbonate sediments, including ooids, which are common in the Lower Head Formation and Goose Tickle group. It could be argued that these were derived from older carbonates of the platformal succession which might have been exposed in association with the Bradore equivalents. However, according to Chow (1980) ooids in the lower platformal succession were cemented together very soon after deposition, and thus are unlikely to have provided single ooids as detritus. Therefore, a source for rounded microcline and silica cemented sandstones cannot be unequivocally identified from siliciclastic sedimentary units currently present in western Newfoundland.

Despite these problems, it is clear that allochthonous Cambrian siliciclastic units seem to closely resemble likely source lithologies for much of the recycled sediment detritus in the Goose Tickle group and Lower Head Formation. The lithologies most likely to have been sources are those now seen in the Summerside, Blow me Down Brook, and Maiden Point formations.

6.4 OPHIOLITES AND VOLCANIC ROCKS IN THE HUMBER ARM AND HARE BAY ALLOCHTHONS

6.4.1 Ophiolites

Within the both the Hare Bay and Humber Arm Allochthons ophiolitic rocks constitute the highest structural slices. In the Humber Arm Allochthon, the Bay of Islands Complex (BOIC) has long been considered a classic example of the complete ophiolite suite, whereas in the Hare Bay Allochthon, only the lower ultramafic parts of the ophiolite are preserved as the White Hills Peridotite. Lithologies within the BOIC include harzburgite, lherzolite, gabbro, trondhjemites and basalt. Chemically, the volcanics vary from basalts to basaltic andesites (Jenner et al. 1991). Previously, the BOIC was thought to have been formed at a mid-ocean ridge, but has now been re-interpreted as having been formed in a back-arc basin (Jenner et al., 1991).

Another high slice within the Humber Arm Allochthon is the Little Port Complex. Dunning et al. (1991) describe the Little Port Complex as 'a structurally complex assemblage of mafic and felsic volcanic rocks and trondhjemite comprising the highest and most westerly structural unit of the Bay of Islands area. Recent detailed geochemical studies (Jenner et al., unpublished data) strongly indicate an island arc origin for the complex. Felsic volcanics in the complex are geochemically similar to the dated trondjhemite, suggesting contemporaneity of volcanism and plutonism. Spatially associated mafic lavas are island arc tholeiites'. The Little Port Complex has been

restricted by Jenner et al. (1991) to include only separate thrust sheets to the west of the main BOIC blocks.

It is important to consider the role of the Bay of Islands and Hare Bay ophiolites in potentially supplying chromite and serpentine detritus to the Lower Head Formation and Goose Tickle group. A complete ophiolite suite, if exposed, might also have supplied mafic volcanic detritus to these units. Stevens (1970) first noted the presence of chromite detritus in western Newfoundland Ordovician sandstones. From this he inferred that ophiolites must have been exposed by the Middle Ordovician. Bradley (1989) quoting the report of chromite in the Goose Tickle group and Lower Head Formation by Quinn (1988) stated categorically that the Ordovician flysch in the foreland basin was derived from the Bay of Islands Ophiolite.

The presence of detrital chromite in Arenig and Llanvirn sandstones of western Newfoundland has been used by several previous workers to infer that the ophiolites were either very close to final emplacement by that time or nad already been obducted (e.g. Stevens, 1979; Ko, 1985; Hiscott, 1978; Bradley, 1989). Stockmal and Waldron (1990) later used the presence of detrital chromite to place constraints on the arrival time of the entire Humber Arm Allochthon.

Chromite is characteristically associated in abundance with the ultramafic part of an ophiolite (see, e.g. Hiscott, 1978). Both Stevens (quoted in Smyth, 1973) and the author have directly confirmed this association with the discovery of grains of chromite included in (chloritised) serpentine grains (see chapter 4, plates 4.9 and 4.10). Serpentine has been observed in both the Lower Head Formation and the Goose Tickle

group (Stevens in Smyth, 1973; Stevens in Neale (1972)) and this study.

Chemical indicators of an ultramafic source are elevated levels of Cr and Ni in the trace element assemblages of sediments (see chapter 5). Botsford (1988) in investigating the shale geochemistry of the Middle Arm Point Formation, which underlies the Lower Head Formation in the Bay of Islands area, has noted that Cr and Ni values remain constant through the Middle Arm Point Formation, but sharply rise near the base of the Lower Head Formation. Botsford (1988) was able to directly relate the presence of Cr and Ni to the presence of heavy mineral silt layers which included detrital chromite and diagenetic pentlandite. This would appear to pin down the appearance of an ultramafic source to approximately the base of the Lower Head Formation in the Bay of Islands area (upper Arenig).

Since clearly the existence of ultramafic detritus in the Goose Tickle group and Lower Head Formation is considered a key element in building a tectonic model, and since it appears to have a bearing on the current controversy regarding the timing and mechanism of the emplacement of the allochthons, it is worthwhile to review the possible sources which could have supplied ultramafic material to the foreland basin.

Ultramafic detritus may have been generated in the source area of the foreland basin in a number of ways:

1. Exposure of the Bay of Islands and/or Hare Bay ophiolites;

2. Exposure of ultramafic material along emplacement related faults within the Humber Arm and/or Hare Bay allochthons;

3. Ultramafic material exposed under compression within an arc terrane;

4. Ultramafic material erupted in the forearc area of a subduction zone;

6.4.1.1 Exposure of the Bay of Islands and/or Hare Bay Ophiolites

Bradley (1989) has stated specifically that chromite in the foreland basin was derived from the Bay of Islands Ophiolite. The ultramafic part of an ophiolite, which is presumably the main supplier of abundant chromite, lies approximately 7 km below the surface (assuming normal oceanic crust). Dunning and Krogh (1985) documented Lower to Middle Arenig age dates for formation for the BOIC. If normal oceanic crust and simple vertical uplift is assumed, the ophiolite would theoretically have been uplifted a minimum vertical distance of 7 km during the Arenig to bring ultramafic material to the surface. In order for supply of ultramafic detritus to the earliest Lower Head sandstones in the late Arenig, the ultramafic material must have been uplifted above sea level, which would imply an uplift of another 3 to 4 km. The ophiolite would have had to have been formed (485 my - Dunning and Krogh, 1985), and its ultramafic part uplifted and exposed within as little as 9 my (latest Arenig is 476 my, Harland et al., 1990) This may be an unrealistic expectation.

If the ophiolite underwent simple vertical uplift, evidence of gradual unroofing might be expected in any sediments which received detritus from the gradually emerging ophiolite. This may be difficult to corroborate since it is difficult to specify whether a particular volcanic grain of sand has been derived from an ophiolite suite or other volcanic unit (see discussion below). Other ophiolitic lithologies, including gabbro and trondhjemite, might be equally problematic since both of these are coarse grained

lithologies and it would be difficult to identify contributions from these in fine grained sandstones. Nevertheless, mafic volcanic detritus is clearly not abundant in the Goose Tickle group and Lower Head Formation.

Published structural configurations (e.g. Williams, 1975; Cawood, 1990) would suggest that the ophiolite was right way up throughout the emplacement process i.e. overturning, imbrication or other anomalous exposure of the lower parts of the ophiolite is not implied. However, all massifs which constitute the Bay of Islands Ophiolite have a synclinal structure. This has previously been interpreted as early deformation which occurred prior to complete assembly and emplacement of the Humber Arm Allochthon (Williams, 1973). This early folding could have tilted the blocks such that the ultramafic parts might have been exposed. However, Cawood (1990) has suggested that the folding could in fact postdate Taconic emplacement, which would remove that possibility.

Casey and Kidd (1981) suggested that at least one part of the Bay of Islands Ophiolite was tilted and subaerially exposed relatively early. The ophiolite is inferred to have been exposed during the late Llanvirn, subsequent to the formation of the dynamothermal aureole at the base of the ophiolite (469 my, Dallmeyer in Dunning and Krogh, 1985 - recalculated age from Dallmeyer and Williams, 1975). The ophiolite was subsequently submerged, again during the Llanvirn.

The evidence (detailed in Casey and Kidd, 1981) for this comes from an area in the Bay of Islands, where a relationship is preserved in which the tilted Bay of Islands Ophiolite shows an erosion surface with considerable relief (300 m) marked by extensive intense weathering and soil formation. Submarine breccias overlie this unconformity,

and these breccias are overlain by grey mudstones which contain marine fossils of Llanvirn age. Clasts in the breccias do include ultramafic rocks, but these are by far the rarest type associated with this unit. The breccias also include clasts from the metamorphic aureole dating them as having formed subsequent to the aureole, suggesting that at least part of the ophiolite must have been above sea level by 469 my.

The highest unit in the sedimentary succession overlying the ophiolite is a unit of red, coarse grained sandstones which are cross-bedded in places (Casey and Kidd, 1981) and may be shallow marine or terrestrial. Sandstones collected by the author from this unit contain framework grains which are predominantly hematised volcanic clasts with aligned plagioclase phenocrysts (trachytic texture). No serpentine or chromite grains were observed. Grains are cemented by calcite. A sample from these sandstones was geochemically analysed and contained low values of Cr and Ni, supporting the petrographic evidence of low or no input from ultramafic sources.

The above relationships, which are rather tightly constrained, imply that at least part of the Bay of Islands Ophiolite was uplifted by the latest Llanvirn, and the structural configuration is such that ultramafic rocks could have been exposed to provide detritus, although they appear to have been only minor suppliers of detritus locally.

However, these relationships provide no evidence of exposure of the ophiolite during the Arenig or early Llanvirn, when the Lower Head Formation and the Goose Tickle group respectively were being deposited.

A note of caution should be applied in evaluating the above arguments, as errors on the absolute dates of Ordovician age boundaries are comparable to the lengths of the

ages themselves (DNAG time scale, 1983).

Regardless of whether the BOIC was exposed during the Arenig, it is unlikely to have provided detritus to the northern part of the foreland basin, since transport along the basin was towards the south. However, there is evidence that the Hare Bay Ophiolite may have been exposed earlier than the Bay of Islands Ophiolite. The age of the metamorphic aureole in the Hare Bay Ophiolite is older than that of the Bay of Islands ophiolite (489 my). Equivalents of this peridotite could have been exposed near the northern part of the basin during the Arenig and Llanvirn to provide chromite and serpentine detritus which was then longitudinally transported to all parts of the foredeep and trench slope basins.

6.4.1.2 Emplacement Related Faults

Both Tuke (1966) and Cawood (1990) have stated that emplacement of upper structural slices of the allochthons was probably lubricated by serpentinite. Occurrences of serpentinite along faults are a well documented feature at various localities associated with ophiolite emplacement (Lockwood, 1971; Saleeby, 1981). Ultramafic material associated with such faults would likely be emplaced by a combination of tectonic processes and diapiric movement. It is therefore possible that the chromite and serpentine could have been derived from ultramafic 'protusions' (Lockwood, 1971) along faults which were active prior to final emplacement of the ophiolites. No evidence has been found in this study which either supports or refutes this possibility.

6.4.1.3 Material from the Base of an Arc Terrane

In the classic area of the Sierra Nevada, California, ultramafic material, which was formerly the base of a volcanic arc, has been faulted upwards in a compressional regime to become associated at the surface with its andesitic cap (Moores and Day, 1984 - see figure 6.8)). In general ophiolitic rocks exposed along faults in the area are dominated by ultramafic material, emplaced by a combination of tectonic and diapiric processes. Thus a volcanic arc terrane exposed in a compressed and uplifted source area could have provided ultramafic detritus to the foreland basin.

6.4.1.4 Serpentine Volcanoes in a Forearc Region

Fryer et al. (1989) and Fryer (1992) have investigated occurrences of submerged serpentine seamounts in the forearc area of the Marianas trench. The serpentine occurs in a variety of forms, from massive serpentinised peridotite to unconsolidated serpentine mud volcanoes. The serpentine mud may contain blocks of peridotite and various types of volcanic rocks as well as chert. Some of the volcanic rocks clearly have island arc affinity, but others are mid-ocean ridge basalts. The massive serpentine is inferred to have been transported to the surface from the underlying mantle through diapiric intrusion along faults. The mud material was emplaced through a combination of grinding into 'rock flour' and diapiric intrusion.

The serpentine in the Lower Head Formation and Goose Tickle group, while altered, appears to have been supplied as grains of sand size, and there is no evidence for abundant serpentine mud in either of these units. Although the discovery of

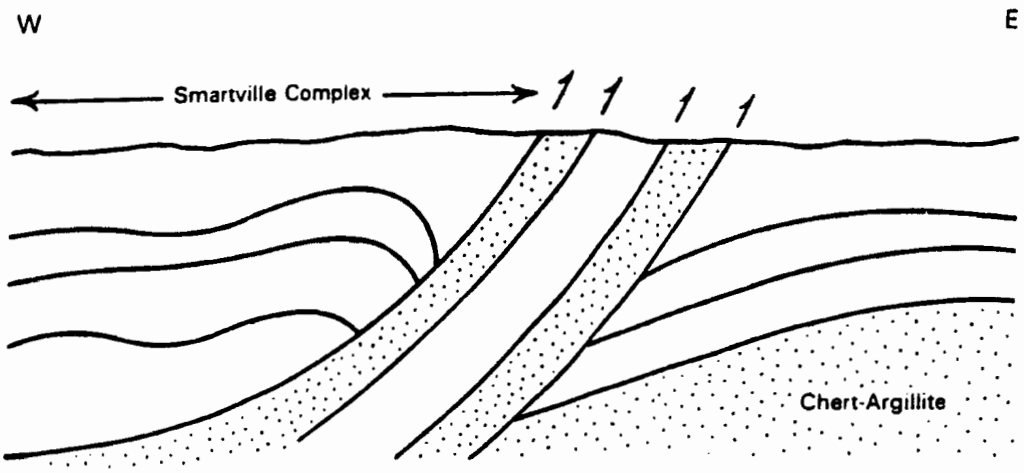


Figure 6.8: This figure shows a cross section through the Smartville Belt, Sierra Nevada, California, after Moores and Day (1984). The Smartville Belt consists of a sequence from bottom to top, of minor layered gabbro, massive gabbro and trondhjemite, a sheeted dike complex, pillow lava and andesitic volcaniclastic sedimentary rocks. It is interpreted as an oceanic island arc - marginal basin complex. Under compression this terrane has been involved in thrust faulting. The thrust faults shown in the diagram are marked by ultramafic material, and are typical of thrust faults throughout the Sierra Nevada. Ultramafic bodies along thrust faults in the Sierra Nevada can be several kilometers wide, and 10's of kilometers long (R.K. Springer, pers. comm., 1992). This provides a mechanism whereby abundant ultramafic material can be associated at the surface with felsic and intermediate volcanic material, thus eliminating the need for unroofing of a complete ophiolite complex to generate ultramafic detritus. The surface width of the Smartville Complex in this cross section is about 30 km.

serpentine mud volcanoes means that 'ultramafic detritus is potentially available at any consuming plate margin and uplift and erosion are unnecessary' (examiners comment - Colman-Sadd, 1992), a means of transporting the grains in a submarine setting and mixing the ultramafic detritus with other types of detritus is required in the case of the western Newfoundland foreland basin. It seems that only the massive serpentine bodies could have supplied sand-sized grains as detritus, and would have had to be uplifted and eroded to do so. In view of these points it is hard to envisage serpentine material from this setting being supplied to the foreland basin without prior uplift and erosion.

6.4.1.5 Evaluation of Potential Ultramafic Sources

For the Goose Tickle group and Lower Head Formation in western Newfoundland, it is difficult to establish which of the types of sources of ultramafic material listed above might have been responsible for the detritus in these units. Derivation from the Bay of Islands Ophiolite is unlikely because of its position south of a major part of the basin, and because a source which was composed predominantly of ultramafic material would better explain the lack of evidence of unroofing of a complete ophiolite sequence. Derivation from the Hare Bay Ophiolite is possible, however, since it is unknown whether the peridotitic part of the Hare Bay Complex ever had a mafic cap. Serpentine lubricated faults and serpentine seamounts are both possible but the author favours the hypothesis of ultramafic material associated with a major arc terrane, as this would best explain the association of felsic volcanic material (which is apparently exotic to the allochthons - see section 6.4.2) with ultramafic material.

6.4.1.6 Implications for Timing of Emplacement of Allochthons

The most compelling evidence for timing of arrival of the allochthons was previously considered to be the overlapping relationship between the neoautochthonous Long Point Group and the Lower Head Formation on the Port au Port Peninsula. This bracketed the time of final emplacement of the Humber Arm Allochthon within the Middle Ordovician, based on the assumption that the Humber Arm and Hare Bay allochthons were emplaced as a single pre-assembled stack (e.g. Williams, 1975). Cawood and Williams (1988) and Cawood (1990) suggested that the allochthons were not emplaced as single stacks but that the ophiolites arrived at their present positions subsequent to the emplacement of the sedimentary parts of the allochthons, possibly during the Silurian or Devonian. This hypothesis echoed those of Tuke (1966, 1968), and Schillereff (1980) who had implied that the sedimentary slices of the Hare Bay and Humber Arm allochthons respectively were in place prior to the final emplacement of the ophiolites.

With these ideas and the reinterpretation of the contact between the Lower Head Formation and the Long Point Group as a thrust (Stockmal and Waldron, 1990), the question of timing of arrival of the allochthons was reopened. To resolve this question, Stockmal and Waldron (1990) suggested that the presence of chromite detritus in Middle Ordovician sandstones of the Mainland formation, as reported by Stevens (1970) and Quinn (1988), constitutes the only remaining evidence for a Middle Ordovician emplacement date for the allochthons, based on the argument that the allochthons were emplaced as a complete package of sedimentary slices and ophiolites.

The timing of arrival of the lowest sedimentary slices of both the Humber Arm and Hare Bay allochthons can be inferred as Middle Ordovician from the evidence provided by the Howe Harbour Member (see chapters 2 and 3), similar lithologies have been recognised by Waldron and Stockmal (1991) in the Victor's Brook area of the Port au Port Peninsula. However, given the discussion above of potential sources of ultramafic detritus, it is clear that the presence of chromite in the Lower Head Formation and the Goose Tickle group does not constrain the timing of approach of the ophiolite, and the argument of Stockmal and Waldron (1990) is undermined. The hypothesis of Cawood and Williams (1988) and Cawood (1990) for Silurian or Devonian final emplacement of the ophiolites would appear at this point to have the greater weight of supporting evidence.

6.4.2 Volcanic Rocks

6.4.2.1 Mafic Volcanic Rocks

Any discussion of the Taconic allochthons as possible sources for detritus in Ordovician sandstones must include a complete evaluation of volcanic rocks within the allochthons. Volcanic rocks, the majority of which are mafic, occur in a number of different structural settings within the Taconic allochthons:

Setting 1. Pillow lavas associated with the ophiolite itself;

Setting 2. Discrete slivers and megablocks of structurally sub-ophiolitic volcanic rocks which occur along the eastern and southern margins of the ophiolite in the Humber Arm Allochthon (e.g. Baker, 1978; Godfrey, 1983; Schillereff, 1980; Quinn, 1985);

Setting 3. Volcanic rocks of the Little Port Complex.

In the Humber Arm Allochthon the volcanics from setting 2 occur in at least two structural positions, both closely associated with the Blow me Down Brook Formation:

a) at the structural top of the formation, directly beneath the ophiolite;

b) near the basal thrust which separates the Blow me Down Brook from other sedimentary units in the Humber Arm Allochthon;

Probably the best known example of the high volcanic slices (type a) directly beneath the ophiolite is the Skinner Cove Formation, a distinctive alkaline suite of relatively unaltered rocks interpreted by Baker (1978) as a unit, chemically unrelated to the Bay of Islands Ophiolite, which originated at an oceanic seamount. Although the Skinner Cove volcanics are closely associated with fossils of Ordovician age, Baker (1978) interpreted this association as tectonic, thus the age of the Skinner Cove volcanics is unknown. Jenner et al. (1991) have confirmed a relationship between Skinner Cove volcanics and other volcanics in high slices in the Humber Arm Allochthon.

Quinn (1985) noted the presence of volcanics which occur at the structural base of the Blow me Down Brook Formation (type b). The question of whether there is a stratigraphic relationship between these volcanic rocks and the Blow me Down Brook Formation is a controversial one. There is some evidence of such a stratigraphic relationship on Woods Island (Appendix 1, location map 2), where volcanic rocks are apparently overlain by the Blow me Down Brook Formation (Williams 1973; Kidd and Idleman 1982). Gonzalez-Bonorino (1979) and Stevens (R.K. Stevens, pers. comm. 1988) believed that there is a stratigraphic contact between the Blow me Down Brook

Formation and volcanic rocks on the east side of South Arm, Bonne Bay, although Quinn (1985) disputed this. Botsford (1988) cited an example of volcanic rocks associated with the Summerside Formation, a unit which is probably partially or wholly equivalent to the Blow me Down Brook Formation.

Supporting evidence for volcanic rocks of at least two different origins within the lower slices of the allochthons may be obtained by consideration of equivalents of the Blow me Down Brook Formation, such as the Maiden Point Formation in the Hare Bay Allochthon. The Maiden Point Formation includes near its structural base tholeiitic mafic volcanics showing geochemical affinities to the rift related Lighthouse Cove Formation (Williams and Smyth 1983; Jamieson, 1976). Alkaline rocks of different geochemical affinities intrude the Maiden Point Formation near its structural top and may be geochemically related to the Skinner Cove Formation (Jamieson, 1976). They are chemically unrelated to structurally overlying ophiolitic rocks (Jamieson, 1976), but they are chemically related to separate and dismembered volcanic slices which are structurally directly underneath the ophiolite.

The presence of tholeiitic volcanics at or near the bases of the Maiden Point and Blow me Down Brook formations may be related to rifting processes along a young continental margin, but Lindholm and Casey (1989) have disputed this. They argued that as the Blow me Down Brook Formation was deposited under deep marine conditions, the rifting process must have been completed by the time of deposition of the unit, and that rift related volcanics were therefore unlikely to be associated with the unit. They also noted that volcanic detritus is absent in the Blow me Down Brook Formation, which they

felt precluded any stratigraphic association with volcanic rocks. However, Lindholm and Casey (1989) did not include an evaluation of the better documented relationships in the Maiden Point Formation in their discussion, nor did they point out that the parautochthonous Bradore Formation, which is clearly associated with rift related volcanic rocks, is largely devoid of volcanic detritus.

Volcanics in the Little Port Complex are considered to be arc related and older than the Bay of Islands Ophiolite (Dunning et al., 1991). It is tempting, in view of the reinterpretation of the Bay of Islands Ophiolite (Jenner et al., 1991) and the westerly structural position of the Little Port Complex (Cawood, 1990; Jenner et al., 1991), to consider the Little Port Complex as a possible remnant of an arc which was located on the foreland (west) side of the back arc basin which eventually produced the Bay of Islands Ophiolite. Mafic, felsic, and plutonic rocks of Little Port equivalents might thus have been structurally well situated to provide detritus to the Lower Head Formation and Goose Tickle group.

As a result of the above discussion it is therefore possible that at least four mafic volcanic sources from within the allochthons could have provided detritus to the Goose Tickle Group and Lower Head Formation:

1. Ophiolitic volcanics;

2. Volcanics, possibly related to a late phase of rifting, stratigraphically associated with the Blow me Down Brook and Maiden Point formations;

3. Assorted tholeiitic and alkaline volcanics now preserved as high slices within the allochthons and possibly formed in an oceanic seamount setting;

4. Arc-related rocks of Little Port Complex equivalents.

All of these mafic rock types would be difficult to distinguish when preserved only as sand-sized grains. This discussion shows that there are several possible non-ophiolitic sources for the rather small number of mafic volcanic fragments in the Goose Tickle group and Lower Head Formation.

6.4.2.2 Felsic Volcanic and Plutonic Rocks

The only possible source in the allochthons for felsic rock fragments found in the Goose Tickle group and Lower Head Formation is the Little Port Complex. However, the proportion of felsic rocks in the Little Port Complex does not seem sufficient to account for all of the observed felsic detritus. As stated in the previous section, an arc related to the Little Port Complex might have been in structurally favourable position to provide detritus. But numerous arc terranes might have been available to provide detritus (e.g. Fyffe and Swinden, 1991). It is here suggested that the felsic detritus was most likely derived from an arc terrane under compression in the source area, possibly, but not necessarily one related to the Little Port Complex.

6.5 FLEUR DE LYS SUPERGROUP

The Fleur de Lys Supergroup has been described as a sequence of metasedimentary rocks (Hibbard, 1983) which may have similar origins to the Blow me Down Brook and Maiden Point formations. The Fleur de Lys Supergroup was described by Schwab (1991) as being quartz rich and having a high ratio of potassium feldspar to

plagioclase, in contrast to the Blow me Down Brook and Maiden Point formations. It would be interesting to know the origins of the potassium feldspar in the Fleur de Lys Supergroup, for if original plagioclase has been altered to potassium feldspar by metamorphic processes, then a possible source for potassium feldspars in the Goose Tickle group and Lower Head Formation may have been identified. Crucial to this argument is some knowledge of the timing of metamorphism of the Fleur de Lys Supergroup. It has been suggested by Dunning et al. (1990) and Waldron and Milne (1991) that peak metamorphism in Fleur de Lys equivalents was of Silurian age or older. Thus it is unlikely that metamorphosed Fleur de Lys lithologies may have provided detritus to the Goose Tickle group and Lower Head Formation. However, this hypothesis requires further investigation.

6.6 DUNNAGE ZONE

The Dunnage Zone is a predominantly volcanic terrane containing a complex assemblage of rocks of both arc and non-arc affinities (Dunning et al., 1991) ranging from Cambrian to post-Middle Ordovician in age and probably representing a complex series of collisions of various arc segments along subduction zones of unknown and possibly variable polarity. Structural and stratigraphic evidence (Williams and Hatcher, 1983) indicates that the western part of the Dunnage Zone (Notre Dame Subzone) was in proximity to the western Newfoundland foreland basin. In fact, ophiolites of the Taconic allochthons are now viewed by some authors (e.g. Williams et al., 1988) as having been continuous with the Notre Dame Subzone before dissection by erosion.

However, the details of this are debatable, as paleontological evidence (Nowlan and Barnes, 1987) suggests that the Taconic allochthons (and therefore presumably the ophiolites) may not have extended much farther than their present areal limits. Given the close relationship between ophiolites of the Notre Dame Subzone and those of the Taconic allochthons, the distinction of Dunnage rock fragments from fragments of the Taconic allochthons in sandstones would likely be impossible. However, the structural configuration of the region suggests that the Notre Dame Subzone was located on the 'other side' of an uplifted area which supplied detritus to the foreland basin, and may have been less likely to supply detritus than units which are now between the Dunnage Zone and the remnants of the foredeep basin.

6.7 GRENVILLE BASEMENT

Grenville basement is presently uplifted in the Long Range Inlier and has been thrust westwards over the Humber Arm Allochthon. Grenier (1990) has suggested that this uplift and thrusting took place during the Acadian Orogeny, and thus the Long Range Complex would be unlikely to have provided detritus to the Goose Tickle group and Lower Head Formation.

However, it might be argued that basement could have been uplifted to the east of the foreland basin. It is admittedly be difficult to distinguish first cycle from second cycle Grenville detritus, however, certain plagioclase feldspars are present in Ordovician foreland basin sandstones which resemble those in the Blow me Down Brook Formation. They have clearly been albitised at temperatures below metamorphic levels, suggesting

that they were derived from previously buried sediments rather than directly from Grenville basement. However a better understanding of albitisation of feldspars of both Cambrian and Ordovician sandstones is in order before this evidence can be considered unequivocal.

It might be argued that microcline detritus in the Lower Head Formation and Goose Tickle group could be directly derived from the Grenville basement, but the presence of similar grains in sedimentary rock fragments suggests that although the microcline might ultimately have been derived from Grenville basement, it has gone through at least one sedimentary cycle and has become mixed with other detrital elements before deposition in the foreland basin. Microcline could also be derived from the plutonic roots of an arc terrane, or from an as yet unidentified metamorphic terrane. Dating of the microcline grains would go some way towards resolving this question.

For the reasons given, it is therefore suggested that the Grenville basement was probably not a direct supplier of detritus to the foreland basin.

6.8 MISCELLANEOUS SANDSTONES

Two other groups of sandstone, which may be relevant to the ideas outlined in this thesis, were briefly investigated. The first group included sandstones of the Clam Bank Formation, Cow Rocks outcrop (appendix 1, location map 1), and Winterhouse Formation, which are all units younger than the Mainland formation. Petrographic and geochemical information on these sandstones clearly demonstrates their affinities with the Mainland formation (figures 6.9 through 6.12), although the Clam Bank Formation may

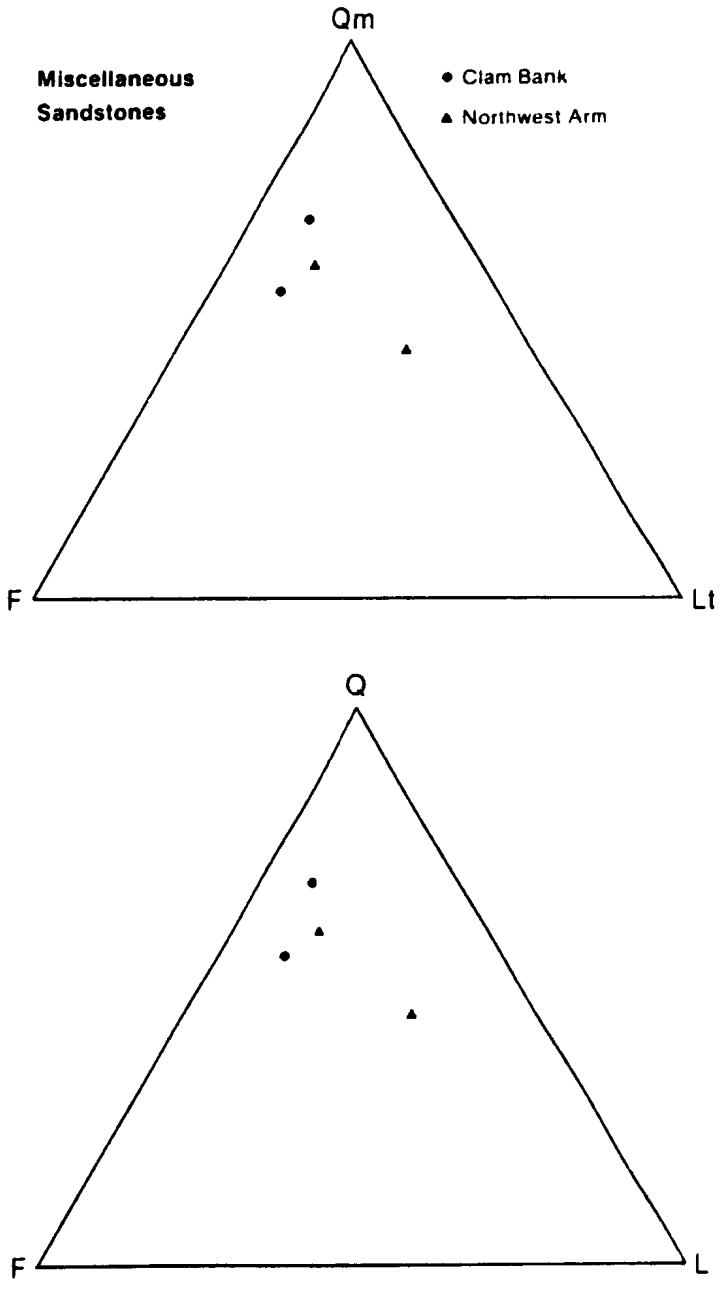


Figure 6.9: QFL and QmFLt diagrams for miscellaneous sandstones.

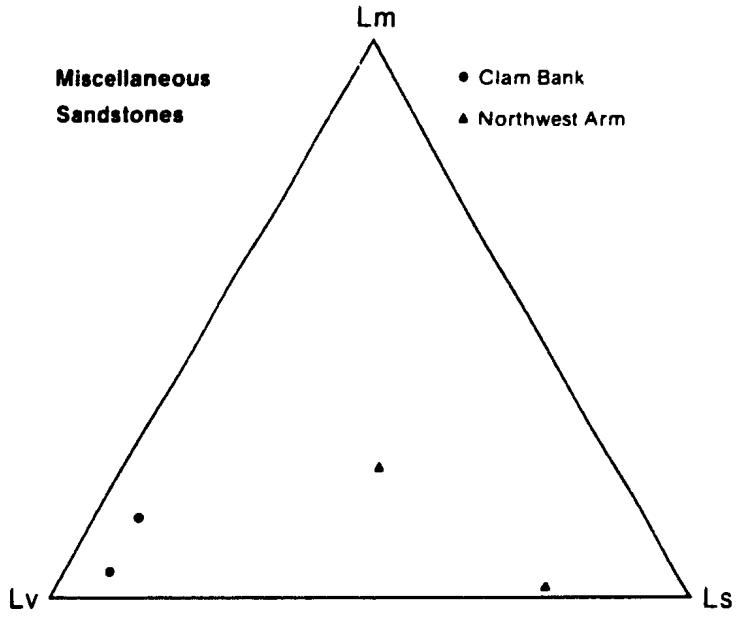


Figure 6.10: LmLvLs diagrams for miscellaneous sandstones.

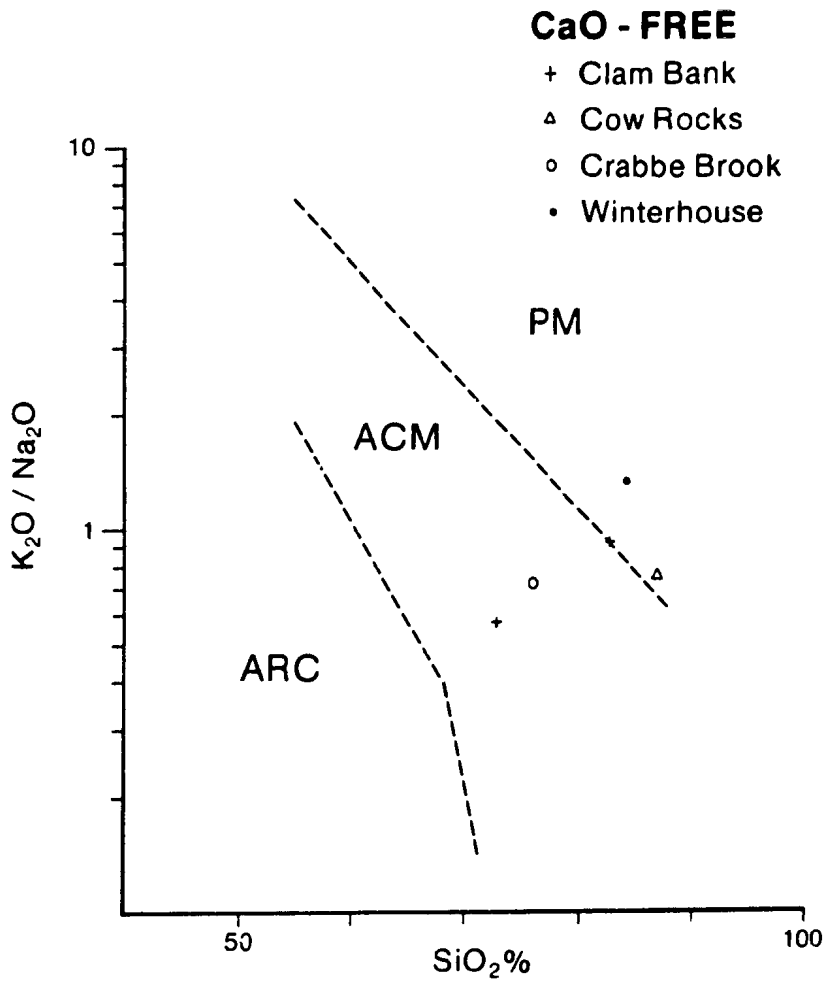


Figure 6.11: Plot of K_2O vs. SiO_2 for miscellaneous sandstones. Fields after Roser and Korsch (1986). Keyed as for figure 6.6.

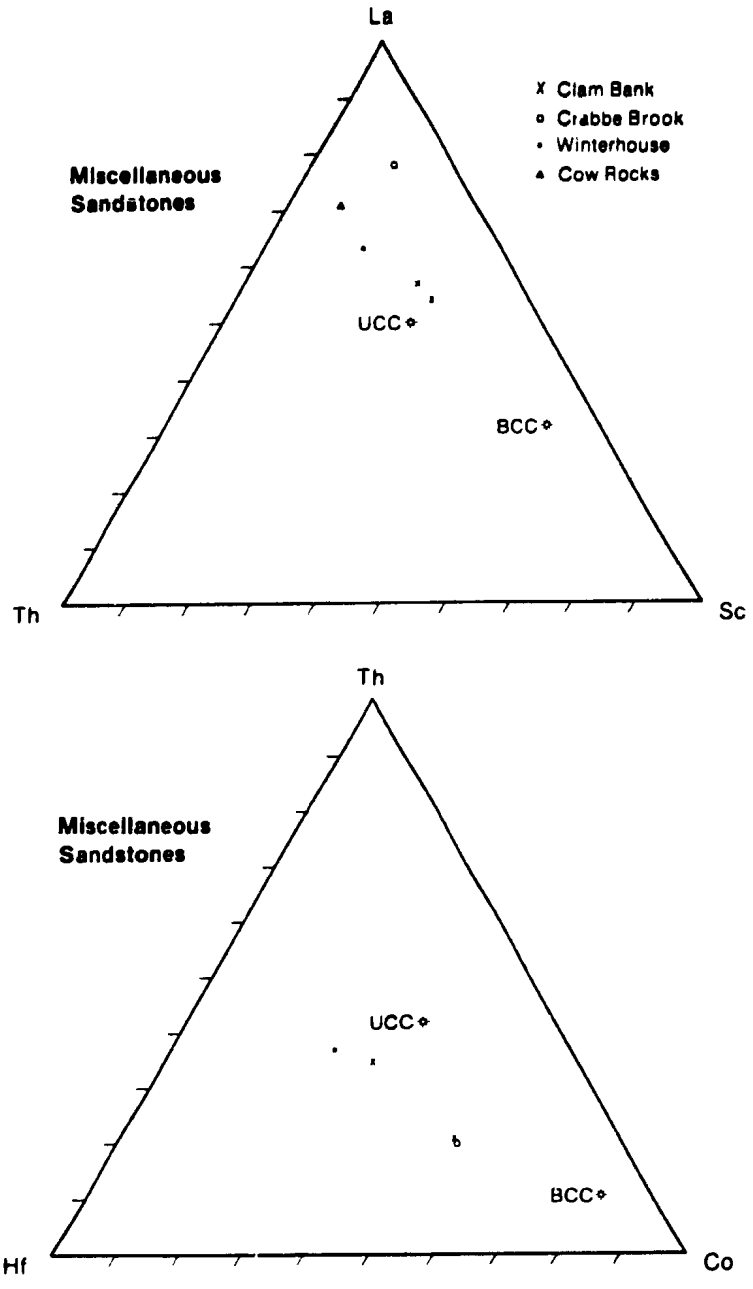


Figure 6.12: Th-Hf-Co and La-Th-Sc diagrams for miscellaneous sandstones.

contain a higher proportion of volcanic rock fragments, suggesting a continued exposure of a volcanic source long after the time of deposition of the Mainland formation, in combination with a reduced input of sedimentary rock fragments derived from the eastern slope of the foreland basin.

The most interesting information is provided by sandstones of the second group, the Northwest Arm Formation. The Northwest Arm Formation is a chaotic unit of black and green shales, limestones and sandstones which constitute the lowest sedimentary slice in the Hare Bay Allochthon. Sandstones in the Northwest Arm Formation are clearly petrographically and chemically identical to those in the American Tickle formation (figures 6.9 through 6.12). The Northwest Arm Formation is considered to be of Tremadoc age (Stevens, 1976), so either sandstone deposition in the foreland basin began significantly earlier than has previously been realised, or the Northwest Arm Formation represents a highly condensed section from the Tremadoc through the Arenig, with American Tickle-like sandstones near the top. Similar condensed sections have been reported in allochthonous units of this time period elsewhere in western Newfoundland (Botsford, 1988). To the author's knowledge, this is the first time the similarities between Northwest Arm sandstones and American Tickle sandstones have been documented and interpreted.

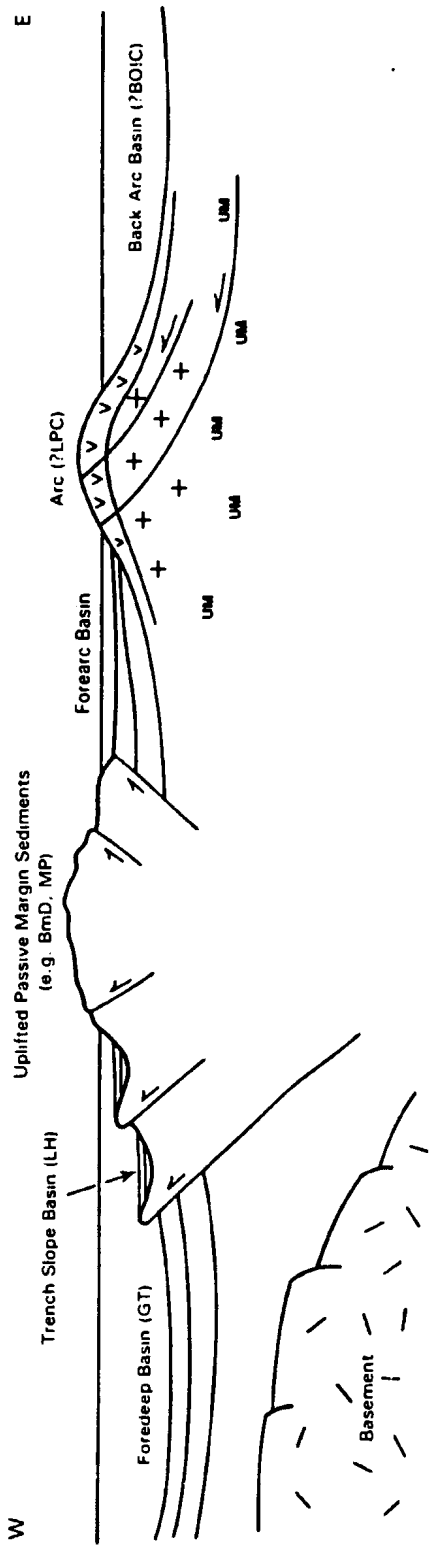
6.9 SUMMARY AND CONCLUSIONS

It is clear from discussions above that the most likely source terranes for extrabasinal framework grains in the Goose Tickle group and the Lower Head Formation

are those which lay to the east and northeast of the foreland basin, since sources from the western margin of the basin are unlikely to have contributed a significant amount of detritus. It is here suggested that the source of felsic volcanic and plutonic grains, as well as ultramafic plutonic fragments, was a major volcanic arc terrane. This terrane may have been located to the west of the back arc basin in which the Bay of Islands Ophiolite was formed (figure 6.13). Mafic volcanic fragments could have been derived from a number of sources including older rift related volcanics. Much of the quartz and feldspar detritus was likely derived from uplifted sediments like the Blow me Down Brook and Maiden Point formations which themselves were ultimately derived from Grenville basement. Rounded resedimented microcline, shallow water carbonates and silica cemented sandstone fragments could have been derived from shelf areas of the basin in which detritus from these multiple sources is inferred to have been mixed. The microcline and sandstone fragments may ultimately have been derived from the plutonic roots of the postulated arc terrane, from Grenville basement and cover, or from an unknown metamorphic terrane.

It is worth noting that although much of the detritus in the Lower Head Formation and Goose Tickle group can be tentatively identified with lithologies now found in the Humber Arm and Hare Bay allochthons, there is no obvious source within either allochthon for abundant rounded microcline, or for the bulk of the felsic volcanic detritus. If sediment was eroded from the allochthons and supplied directly to the basin, material from other sources would be expected to form distinct petrofacies. This has not been observed, and the overall petrographic homogeneity of the units implies that mixing

Figure 6.13: This schematic diagram, modified from Lundberg and Dorsey's (1988) analysis of the Taiwan collision system, shows how detritus within foreland and trench slope basin sediments in the Newfoundland system could have been mixed in a forearc basin and/or an upper trench slope basin could have been recycled into the foredeep basin. In Taiwan, the forearc basin was eventually caught in collision. If a similar scenario existed in Newfoundland, the preservation potential of the forearc basin would have been poor. The Goose Tickle group is inferred to have been deposited in the foredeep basin proper. The Lower Head Formation is inferred to have been deposited in a trench slope basin. The uplifted area to the east of the foredeep basin would have mainly consisted of deep water passive margin sediments, but basement could also have been incorporated. The arc terrane is shown cut by faults under a regional compressional regime. Ultramafic material could have been uplifted along these faults and exposed at the surface to provide ultramafic detritus to the system. This arc terrane may or may not have been related to the Little Port Complex. East of the arc terrane is a back arc basin, which may have been the locus of formation of the Bay of Islands Ophiolite. Note that the inferred width of the Taiwan system from eastern margin of the foredeep basin to the eastern margin of the arc is of the order of 100-150 km.


E
W
Back Arc Basin (?BOIC)
Arc (?LPC)
Forearc Basin
Uplifted Passive Margin Sediments
(e.g. BmD, MP)
Trench Slope Basin (LH)
Foredeep Basin (GT)
Basement
UM
UM
UM
UM

of the detritus has occurred. Hence field evidence that the Goose Tickle group and Lower Head Formation were not shed directly into the foreland basin from the Humber Arm and Hare Bay allochthons is borne out by provenance investigations.

This last point may seem to be overemphasised, but, to the casual reader of west Newfoundland literature, the overriding impression given is that the sands in the foreland basin were derived by direct erosion, lateral transport and deposition of material from the allochthons, and that in particular ultramafic material was derived from ophiolites which we now see exposed in western Newfoundland. In view of the discussions in this thesis, this is clearly a vastly oversimplified scenario.

It should be noted that in order to explain the detrital makeup of the Lower Head Formation and Goose Tickle group, the author has hypothesised two major features which may have lain to the east of the foreland basin:

1. A major arc terrane;

2. A major upper slope or forearc basin in which mixing of detritus from multiple sources must have taken place.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 REVIEW OF THE GOOSE TICKLE GROUP AND LOWER HEAD FORMATION

7.1.1 Stratigraphy

Three units of Ordovician sandstone have been recognised in this study (see chapter 2). Two of the units, the American Tickle formation (Llanvirn) and the Mainland formation (Llanvirn - ?Llandeilo), are parautochthonous, and are at least partial time equivalents. These two units constitute the Goose Tickle group. Formal stratigraphic definitions of these units are pending as a result of this study (Quinn, in prep.). The allochthonous unit is designated the Lower Head Formation (Arenig - Llanvirn), and this name is extended from its original use north of Bonne Bay to describe all equivalents in western Newfoundland.

7.1.2. Sedimentology

All three units defined above consist of sandstones and shales which were deposited mainly from turbidity flows. The American Tickle formation is generally sand-poor, whereas the Mainland and Lower Head formations are sand-rich.

The American Tickle formation extends from the tip of the Northern Peninsula to the Port au Port Peninsula, and is interpreted to reflect deposition in an oversupplied foredeep basin (see chapter 3). Variations in the sand/mud ratio within the unit are interpreted to reflect proximity to sediment input points, of which there were at least two

supplying the northern and central parts of the basin. The Howe Harbour member is interpreted as a coarsening upwards sequence of gravity flow deposits generated by faulting in the source area, and, like the Daniel's Harbour Member, is a precursor to the arrival of the lower slices of the Taconic allochthons.

The Mainland formation, which is restricted to the Port au Port Peninsula, indicates the existence of a third sediment input point at the southern end of the same oversupplied basin (see chapter 3), but this formation was deposited in a tectonically and topographically complex area characterised by lobe switching and reactivation of pre-existing rift-related faults prior to the emplacement of the Humber Arm Allochthon. The Mainland formation in its type area was somewhat removed from the leading edge of the Humber Arm Allochthon, however, it shows abundant evidence of rapid deposition and active tectonism.

The Lower Head Formation represents a series of several submarine fans which were probably deposited in a small trench slope basin or basins. Clast populations within conglomerates in these deposits indicate that the eastern shelf margin of the basin(s) was very narrow, suggesting supply by fan deltas on steep slopes, and that contemporaneous uplift of pre-existing slope/rise sediments was taking place to the east.

Field relationships in all three units do not support the notion of a flysch shed directly from and obtaining its character wholly from the advancing Humber Arm and Hare Bay allochthons.

7.1.3 Petrography

The Goose Tickle group and Lower Head Formation are petrographically similar (see chapter 4) and are in general matrix rich. The units are variably altered, with the American Tickle formation in particular showing considerable replacement of framework grains by calcite. Both fine and coarse grained clay minerals are apparently preferentially replaced by calcite, but feldspar is also frequently calcitised, and less frequently, quartz.

Bulk compositions of the Goose Tickle group and the Lower Head Formation are similar, and all three units are quartz-intermediate to quartz-rich (sensu Taylor and McLennan, 1985), with a high proportion of feldspar relative to similar units elsewhere (e.g. Schwab, 1986), and a low proportion of lithic fragments. Ratios of plagioclase to total feldspar are variable, and feldspars generally are difficult to interpret. Potassium feldspars are predominantly rounded microclines which show central cores or scattered patches of albite. These feldspars could be of metamorphic or plutonic origin. Plagioclase feldspars are unzoned and frequently untwinned. These may have a metamorphic or plutonic origin, and only a few of the plagioclase feldspars likely have a volcanic origin. Lithic fragments are dominated by sedimentary rocks, dominantly mudstones and shales. An unusual feature of all of these units is the abundance of monocrystalline phyllosilicate grains, most of which are interpreted to be chloritised serpentine.

Although there is a general petrographic similarity among all three units, similar. te Lower Head Formation may be considered petrographically distinct from the other two

on the basis mainly of a higher feldspar and lower lithic fragment content.

Detritus was contributed to all units from a variety of sources, both extrabasinal and intrabasinal. Source rocks included:

a. mafic volcanic rocks (extrabasinal);

b. mafic plutonic rocks (extrabasinal);

c. andesitic/rhyolitic volcanic rocks (extrabasinal);

d. felsic plutonic rocks (extrabasinal);

f. cemented quartzofeldspathic sandstones and oolites (extrabasinal);

g. black and green shales (marginal to the basin);

h. low grade metamorphic rocks (extrabasinal);

e. intraformational/intrabasinal sediments;

The petrographic uniformity in these rocks suggests mixing of detritus from different extrabasinal sources prior to transport and deposition into the foreland basin proper, but more subtle compositional variations within the American Tickle and Lower Head formations, may, on further investigation, reflect input of a slightly different grain population different sediment input points.

7.1.4 Geochemistry

The Goose Tickle group and Lower Head Formation are generally similar, but certain features of the geochemistry highlight subtle differences between the two units (see chapter 6). Both units are difficult to interpret using any of the standard variation or discrimination diagrams produced by various authors (Bhatia, 1983; Roser and

Korsch, 1986, 1988). Their high iron and magnesium contents in tandem with their high sodium and potassium contents are distinctive, reflecting their mixed sources. There is a marked effect of grain size in elevating iron and magnesium major element parameters in particular.

Both units contain elevated levels of Cr and Ni, which are generally attributed to a contribution by an ultramafic source. The behaviour of Cr with respect to Ni and to other trace and major elements is different in the Lower Head Formation than in the Goose Tickle Group. In the Lower Head Formation, Cr is strongly correlated with Zr and Hf, as well as being moderately correlated with the rare earth elements. It is not correlated with Ni or with al-alk. Conversely, in the Goose Tickle group, Cr shows virtually no correlation with Zr but shows a strong correlation with Ni. This suggests that in the Lower Head Formation Cr is concentrated mainly in heavy minerals, whereas in the Goose Tickle group Cr may also occur adsorbed onto clay minerals, and hence will have a tendency to behave similarly to Ni. Thus it is suggested that a greater amount of Cr and Ni was provided as dissolved load to the Goose Tickle group, indicating not necessarily an increasing supply of ultramafic detritus to the depositional area, but perhaps a greater degree of weathering in the source area.

The Lower Head Formation shows a linear trend on the La-Th-Sc plot which may indicate the preserved signature of an arc source. A similar trend is not preserved in the Goose Tickle group, which may again suggest the influence of weathering in obscuring the signature of the source in the Goose Tickle group.

Rare earth element patterns are variable for individual samples, but all units show

enrichment of LREES and a negative Eu anomaly, typical of passive margin sedimentary rocks, again reflecting the mixed geochemical signatures of these rocks.

7.1.5 Provenance

The simplest explanation for the origin of the mafic volcanic fragments in the Goose Tickle group and Lower Head Formation is that they were supplied by an ophiolite; However, although mafic volcanic fragments are present in the Goose Tickle group and Lower Head Formation, they are far outnumbered by grains of chloritised serpentine, and seem depleted in comparison with what might be expected from material derived from an exposed complete ophiolite. A similar observation was also made by Hiscott (1978). As has been described in chapter 6, there are a number of possible sources for mafic volcanics besides the basalts of an ophiolite, including seamount and rift volcanics, and it is possible that none of the mafic material was supplied by an ophiolite.

Andesitic/rhyolitic volcanics are thought to have been derived from an island arc which was located to the east of the foreland basin (figure 6.13). The extent of rhyolitic material as a contributor to the sandstones in western Newfoundland has not hitherto been recognised. Felsic plutonic rocks may have been derived from the plutonic roots of this arc.

Black and green shale chips, despite their similarity to lithologies currently interbedded with the sandstones, have undergone a greater degree of diagenetic alteration than the sandstones themselves, and must therefore represent material eroded from the

eastern margins of the foredeep, providing independent evidence (other than chromite) that the sandstones were derived from the east. These detrital components are instrumental in recording the arrival of the sedimentary parts of the allochthons in middle Ordovician time.

Ooids and clean, quartz cemented sandstones and siltstones may have been derived from shelves fringing the uplifted source area. Their scarcity suggests that these shelf areas were not very extensive, and they were unlikely to have been marginal to the foreland basin, but instead fringed a basin closer to the uplifted area. Alternatively they may represent cover to Grenville basement which was uplifted somewhere in the source area.

Intraformational/intrabasinal clasts are interpreted as rip-up clasts from immediately underlying sediments.

The abundance of ultramafic detritus relative to mafic material is notable. The ophiolite may have been exposed and oriented in such a way that it supplied only ultramafic detritus to the sediments, as suggested by Hiscott (1978). It is also possible that only ultramafic material was exposed at the time of deposition of the sandstones. A number of ways of achieving this have been outlined in chapter 6. The favoured hypothesis is that compression within an arc terrane exposed ultramafic parts of their roots, similar to documented occurrences in the Sierra Nevada of California (Saleeby, 1981). These features would then have been subject to erosion and could acted as a source of serpentine and chromite, which might be found without associated mafic detritus, but with felsic detritus.

The origin of the quartz and feldspar in the Goose Tickle group and Lower Head Formation is the most problematic aspect of all. The bulk of the evidence suggests that most single feldspar grains do not originate from a volcanic source, but from a metamorphic or plutonic source, and a number of the plagioclases may also have been derived from recycled sedimentary sources. For the plagioclase the author favours dual sources, one from recycled sediments similar to the Blow me Down Brook, Summerside, and Maiden Point formations now found in the Humber Arm and Hare Bay allochthons, and the second from plagiogranite similar to that found in rock fragments in coarser samples.

For the rounded potassium feldspar, a metamorphic or plutonic source is favoured. Possibilities include the plutonic roots of the arc terrane, Grenville basement and/or cover uplifted in the source area, or a hitherto unidentified metamorphic terrane.

Both field relationships and provenance studies suggest that the the Humber Arm and Hare Bay allochthons in western Newfoundland could not have been the sole providers of detritus to the Ordovician sandstones. It is clear that sedimentary units similar to some of those now found in the allochthons may have provided the bulk of the quartzo-feldspathic detritus. Evidence indicates that the sediment was not shed directly off the Humber Arm and Hare Bay Allochthons but was trapped and mixed in a now destroyed basin prior to its deposition in the lower trench slope and foreland area.

7.2 COMPARISONS WITH OTHER UNITS IN THE APPALACHIAN FORELAND BASIN

The general petrographic characteristics of the Goose Tickle group and Lower Head Formation are comparable with those quoted for other units within the Canadian Appalachians (e.g. Hiscott, 1984; Schwab, 1986). Units from the U.S. Appalachians do not contain serpentine, and chromite is much less abundant (D. Rowley, pers. comm., 1985), a feature which is also reflected in their chemistry (Hiscott, 1984).

The most notable aspect of the Goose Tickle group and Lower Head Formation in comparison to other units from the Appalachian foreland basin is in the relative abundance of feldspar, and relative paucity of lithic fragments. Several factors could account for this. Some of these are methodological. Compilations such as those of Schwab (1986), and Hiscott (1984) do not provide information as to the point counting methodology used in individual cases. If the Gazzi-Dickinson method is used, this will tend to move the results away from the lithic pole. If a dual staining method (for potassium and plagioclase feldspar) is not used, an underestimation of plagioclase feldspar content can occur, through difficulties in identifying untwinned plagioclase.

Comparisons of this work with the work of Schwab (1991) on the same units in western Newfoundland, despite his errors in equating autochthonous and allochthonous sandstones, show similarities in feldspar abundances. This suggests that the relative abundance of feldspars in the Goose Tickle group and the Lower Head Formation reflects real differences (the greater importance of a plutonic and/or metamorphic source) in the provenance of Newfoundland sandstones from those in the rest of the basin.

The unit most analagous to the Lower Head Formation in terms of age, tectonic position, and proximity is the Tourelle Formation in Quebec (Hiscott, 1977, 1978). The quartz and feldspar, as well as the volcanic and metamorphic fragments in the Lower Head Formation, are very similar in description to those in the Tourelle. The abundance of feldspar is higher, 24% as opposed to 12% in the Tourelle Formation. The other notable difference between the Lower Head Formation and the Tourelle Formation is the abundance of chloritised serpentine, which is not abundant in the Tourelle.

The unit most analogous to the Goose Tickle group in terms of tectonic position and proximity (although not age), is the Cloridorme Formation in Quebec. According to Ko (1985) the feldspar content of the Cloridorme is again lower than in the Goose Tickle group. Ko also probed a number of feldspars, and like those of this study, none fell into the volcanic fields on the diagrams of Trevena and Nash (1981). Metamorphic fragments are more important in the Cloridorme Formation, perhaps reflecting the fact that the unit was deposited later, after substantial deformation and metamorphism had taken place in the Appalachian Orogen. Serpentine is important in the Cloridorme Formation reaching up to 8% (Enos, 1969).

In summary, although the Lower Head Formation and Goose Tickle group are petrographically broadly similar to units elsewhere in the Canadian Appalachians and show the mixed provenance of foreland basin deposits in general, the Newfoundland units are distinctly different than their nearest equivalents. In a very long foreland basin such as the Appalachian basin, this is to be expected rather than otherwise (see e.g. Lash, 1987), particularly in view of Bradley's (1989) suggestion that a different arc collide with

the margin in Newfoundland, than collided with the rest of the Appalachian foreland basin. If the author's suggestion of an association between ultramafic and felsic fragments in an arc terrane is correct, the greater proportion of plutonic fragments as well as the presence of ultramafic fragments may imply a greater degree of compression (to produce ultramafic material) and unroofing (to produce plutonic material) in the arc terrane which fed the northern parts of the Appalachian foreland basin. If the feldspars are of metamorphic origin, this could mean a greater degree of Grenville basement or related cover units in the source area.

7.3 COMPARISONS WITH OTHER FORELAND BASINS

It is now appropriate, having arrived at an interpretation for the general tectonic setting of the Lower Head Formation and Goose Tickle group, to embark on a general discussion on the similarities and differences between the western Newfoundland foreland basin and other selected foreland basins.

7.3.1 The Foredeep Basin

The geology of the Apennine foreland basins has been extensively summarised by Ricci Lucchi (1985, 1986), and provides an excellent model for comparison of the sedimentology of flysch units in general. The Apennine system of basins is built entirely on continental crust, and the thrust belt is structurally overlain by a high allochthonous slice of oceanic affinity. The schematics of subduction and accretion are controversial, but analogies may still be made between the Apennine basins and the

Appalachian basin. Of particular interest in Ricci Lucchi's (1986) paper is his discussion of the complexity of sediment dispersal patterns, and the relationship between satellite basins and the foredeep basin proper.

According to Ricci Lucchi (1986) the foredeep basin proper should show a number of features which are listed and discussed below.

7.3.1.1 Lateral Thickness Variations

Ricci-Lucchi (1986) described wedging of sandstones away from the steep side of the basin (orogen side) towards the ramp (foreland) side. This has not been documented by the author in the western Newfoundland case.

7.3.1.2 Presence of Slide-Slump Features

'Slide-slump bodies' as described by Ricci-Lucchi (1986) are deposited in front of (but not directly on) thrusts. Their maximum thickness occurs in the vicinity of the thrust, and like sand bodies they may wedge out in the direction of the foreland.

The olistostrome which constitutes the Northwest Arm Formation (see chapters 2 and 3) in the Hare Bay Allochthon may represent such a feature. According to Ricci Lucchi (1986) these features may have a lateral extent (along the basin axis) of 20 km, which is not dissimilar to the lateral extent of the Northwest Arm Formation. Again, westward wedging or thinning of the Northwest Arm Formation has not been observed by the author.

Some might argue that the Northwest Arm Formation cannot represent a foreland

basin 'slump-slide' feature, since its Tremadoc age would indicate that it represents passive margin rather than foreland sedimentation; however, new evidence presented in chapter 6 has shown that the sandstones in the upper part of the Northwest Arm Formation are similar in modal composition and chemistry to those of the Goose Tickle group, and therefore the Northwest Arm Formation may represent a condensed section through the transition from passive margin to foreland basin deposition. Botsford (1988) has shown that the passive margin section in equivalent units within the Humber Arm Allochthon is also condensed. Demonstration of a condensed section in the Northwest Arm Formation, however, awaits paleontological evidence.

7.3.1.3 Pelitic Lenses and Drapes

'Pelitic' lenses and drapes may occur in a foreland basin associated in a variety of fashions with turbidites. According to Ricci Lucchi (1986) they are broadly interpreted as slope deposits and are commonly associated with extrabasinal olistostromes at the tops of clastic wedges. Parts of the Northwest Arm Formation may conform to this description since slope sediments (black and green shales) are associated with extrabasinal components (minor volcanic and plutonic blocks). However, the draping relationship between the shales and the turbidites described by Ricci Lucchi (1986) has not been observed in the Newfoundland case.

7.3.1.4 Longitudinal Transport

According to Ricci-Lucchi, sediment from the thrust belt can be transported by

more than one route to the foreland basin: through the foreland; longitudinally; and directly from the thrust belt. A supply route through the foreland is unlikely to be of importance in the Appalachian situation, as this is specific to the Apennines where pre-deformed Alpine rocks existed in the foreland. However, Ricci Lucchi's (1986) model for direct lateral and longitudinal supply of sediment is very similar to that outlined for western Newfoundland in chapter 3, with sediment being supplied to higher, larger slope basins first, and then being funnelled longitudinally, with sporadic direct supply centres at spaced sediment input points.

7.3.1.5 Control of Sedimentation by Transverse Features

In the Apennine basin (Ricci-Lucchi, 1986), transverse structures segment the orogen and are reflected in the sedimentary record by variations in subsidence and thickness along strike. In the Appennine basin the features themselves are not clear, but it is suggested that they were not major strike slip faults, and the movement along them was predominantly vertical (Ricci-Lucchi, 1986).

Such faults may have created zones along which sediment could access the basin, thus controlling sediment input points, and movement along these faults may have generated earthquakes which resulted in sediment failure and consequent release of sediment to the basin. They may also have allowed for the ponding or deflection of turbidity currents.

The existence of transverse features in the western Newfoundland foreland basin cannot be documented solely from the record of sedimentation within the sandstones, as

the evidence for sediment input points along the exposed margin of the basin is limited to variations in the sand/mud ratio. In any case Cawood and Botsford (1991) argued that such cross-strike or transverse discontinuities must be demonstrated to have been active through several phases of an orogenic cycle, such that it can be demonstrated that they are not late stage fault features.

Cawood and Botsford (1991) have inferred the existence of four cross-strike discontinuities in western Newfoundland and these are shown in figure 7.1, along with the possible sediment input points inferred by the author in chapters 2 and 3. It can be seen that there is some agreement between the two models.

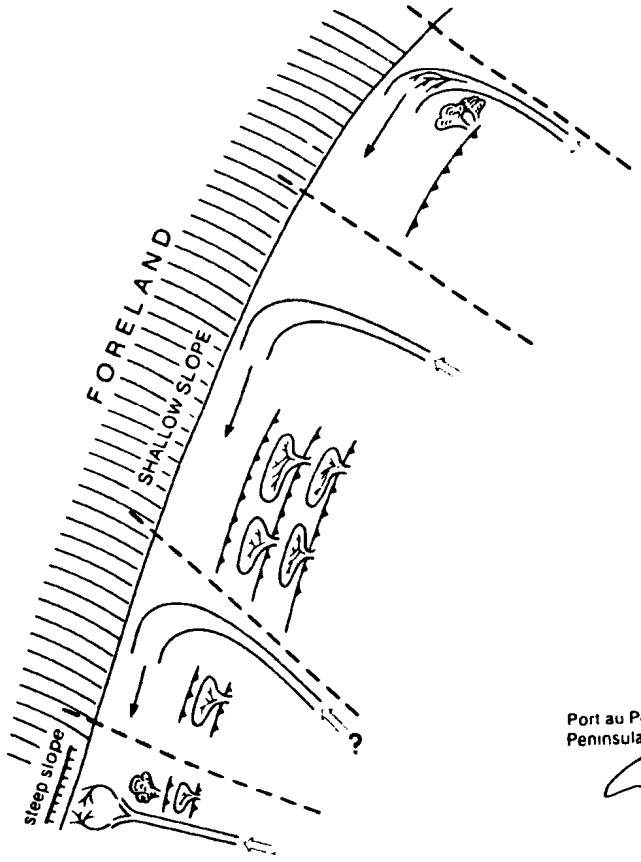
Other evidence for such a lateral transverse feature is at the southern end of the Humber Arm Allochthon, where the deposition of the Mainland formation and the emplacement of the Humber Arm Allochthon (lower slices) may have taken place contemporaneously and the southern termination of the allochthon may have acted as a transverse feature which allowed funneling of sediment into the foredeep basin.

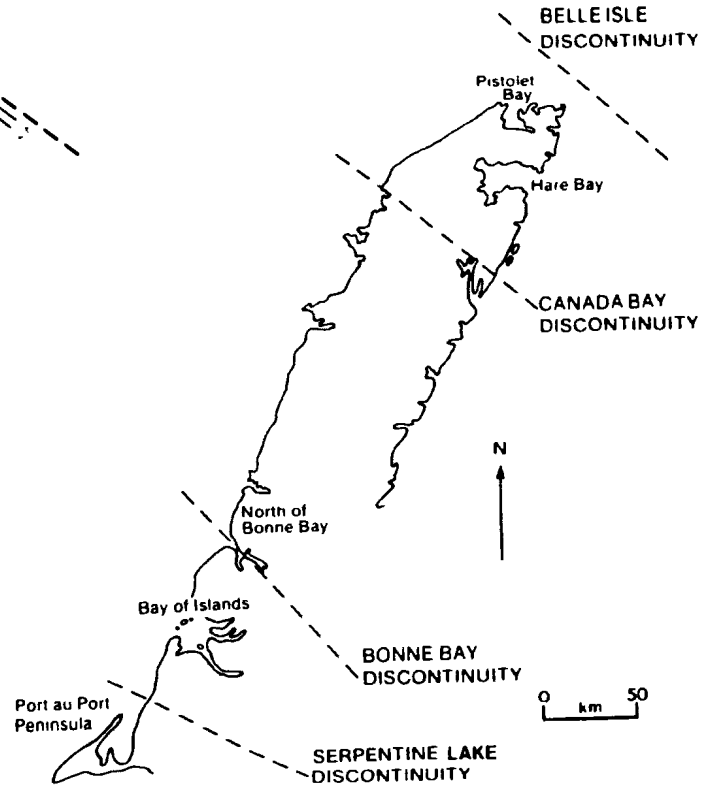
No evidence for axial highs within the western Newfoundland foredeep basin has yet been found.

7.3.2 The Trench Slope, Satellite, or Piggy Back Basin

Ricchi Lucchi (1986) produced a diagram which shows different possible configurations of a foreland basin (figure 7.2). Sub-basins within the foredeep basin may be created either in a sequence (B in figure 7.2) or at the same time (C in figure 7.2) with subequal or different sizes. The term piggyback basin was introduced by Ori and

Figure 7.1 Model for the evolution of the western Newfoundland foreland basin based on interpretations made in this thesis. The location map on the right also shows major structural discontinuities which have been inferred by Cawood and Botsford (1991). The fundamental aspects of the model are: relatively steep slop on the eastern margin of the basin (as compared with Quebec examples); deposition of granule conglomerates, pebble to cobble conglomerates, and olistrostromes in advance of allochthons; locations of at least three sediment input points; presence of slightly older satellite basins fed by sandy fans and bounded by faults; lobe switching and activation of rift related faults in the Mainland area. Note the general agreement of the inferred sediment input points, and the independently inferred structural discontinuities.


FORELAND
SHALLOW SLOPE
steep slope
?


BELLE ISLE
DISCONTINUITY
Pistolet
Bay
Hare Bay
CANADA BAY
DISCONTINUITY
N
North of
Bonne Bay
Bay of Islands
BONNE BAY
DISCONTINUITY
0 km 50
Port au Port
Peninsula
SERPENTINE LAKE
DISCONTINUITY

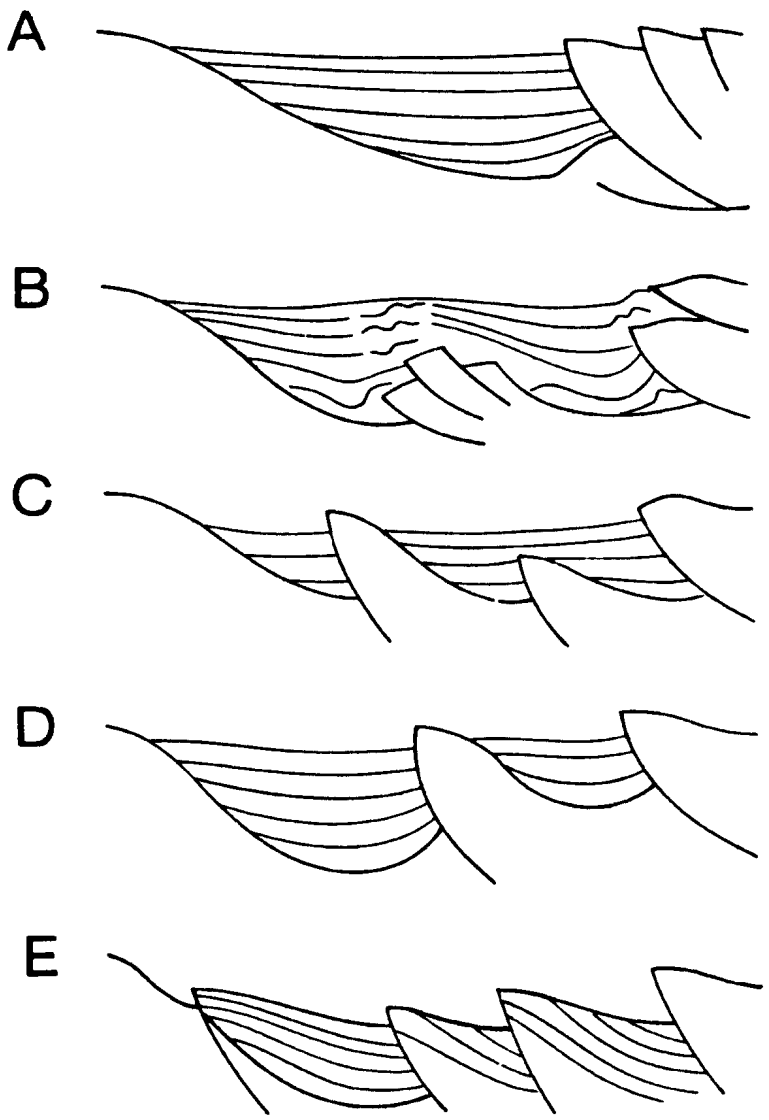


Figure 7.2 Models for the structural evolution of a foreland basin as suggested by seismic records. After Ricci Lucchi (1986).

Friend (1984) to describe a thrust-based basin marginal to a foredeep (D in figure 7.2). Ricci Lucchi (1986) extended the definition to simply include any minor or 'satellite' basin associated with the main foredeep.

Satellite basins should show many of the same features as the main foredeep basin including dominantly turbidite sediments, wedging of sand bodies, slumps-olistostromes, multisourced supply (in part from the same sources), predominance of longitudinal dispersal. With the exception of wedging of sand bodies, the Lower Head Formation shows all of these characteristics.

The satellite basin may also show the following features: rapid lateral facies changes; topographic variations; resedimented deposits are more immature and disorganised; local sources and cannibalised input (including recycling of sand from previous clastic cycles or derivation of material from the basin margin). Lateral facies changes and topographic variations are not well documented, but there is a considerable variability in facies from locality to locality. A greater immaturity of resedimented deposits has not been documented, but local sources and cannibalised input are prominent in the Lower Head Formation.

The evidence appears to be overwhelming that the Lower Head Formation represents a satellite basin or basins peripheral to the main foredeep basin, and formed only slightly prior to the formation of the main foredeep basin. Thus the use of age relationships within the Lower Head Formation to determine whether the sandstone deposition 'transgressed' across the foreland basin is erroneous, as the Lower Head Formation and the Goose Tickle group were not deposited in the same basin. Sandy

sediment was indeed supplied slightly earlier to the satellite basin, and local structural variations allowed for the supply of sediment to different parts of the satellite basin(s) at slightly different times (e.g. Botsford, 1988).

Ricci Lucchi (1986) suggested that different satellite basins may display different provenances, as lateral features may isolate one basin from another. This does not seem to be the case with the Lower Head Formation, where the provenance does not seem to vary significantly from location to location. However, qualitative observations made by the author suggest that subtle variations between localities may occur, and investigation of this must await further study. This is particularly true of the Portland Creek/Portland Hill locality which appeared to contain more fragments of felsic volcanics containing potassium feldspar, and whose sedimentology may be controlled by the transverse feature which marks the northern termination of the Humber Arm Allochthon.

7.3.3 The Entire Foreland Basin System

Ricci Lucchi (1986) suggested that in the interpretation of a foreland basin system two aspects are particularly problematic: how to infer paleotopography from ancient sediments; and how to determine if foredeep splitting took place before or after sedimentation.

7.3.3.1 Paleotopography

According to Ricci Lucci (1986) it is possible to determine the paleotopography of a foreland basin to some extent. Evidence for a slope would include localised sand

lenses, wedging of sands into pelites, and intraformational slumps. On the other hand, parallel layers of great lateral continuity, and particularly megabeds, are taken as evidence of a flat bottom.

Clearly, slope indicators are present in both the Goose Tickle group and the Lower Head Formation, although as noted above stratigraphic and structural control is not sufficient to infer the presence of wedging or sand lenses. No megabeds have been found in either the Goose Tickle group or the Lower Head Formation. This is in contrast to Appalachian foredeep deposits in Quebec, which do show megaturbidites (Hiscott et al., 1986) indicative of a more shallowly dipping eastern margin than that in western Newfoundland.

According to Ricci Lucchi (1986), inferring topography from facies changes and thickness variations in turbidites may not be simple, particularly in the case of a constricted basin such as the western Newfoundland foreland basin. For example, sand-rich horizons interbedded with laterally continuous finer grained deposits might be interpreted as interfingering of lobe deposits (e.g. Ricci Lucchi, 1986), or they might have been caused by variation in subsidence rate generated by thrusting. In addition, sea level changes could also cause these kinds of relationships.

In light of the above statements one cannot be too specific about the interpretation, particularly of the Lower Head and Mainland formations, as submarine fans or complexes of fans since the geometry of those fans cannot be thoroughly documented. In addition, caution must be applied in attempting to extend a model developed at one locality (e.g. Gonzalez-Bonorino (1990) for the Lower Head Formation

at Rocky Harbour) to an entire basin.

7.3.3.2 Foredeep Splitting

Complex foredeeps (B in figure 7.2) are those with thrusts active in their substratum, and it is here suggested that the abundant evidence for syndepositional deformation in both the Goose Tickle group and the Lower Head Formation as well as the near-contemporaneity of the two units qualifies the basin system in western Newfoundland for the title 'complex'. Specific aspects of basin evolution have varied along the length of the foreland basin in western Newfoundland. These will be discussed further below.

Ricci Lucchi (1986) warned that many obscure unconformities may be present in the sediments of satellite basins. These can include erosional surfaces, angular contacts and lithofacies changes. In the Lower Head Formation, this appears to be entirely possible, as the history of events outlined in chapter 3 suggests. An unconformity may exist between the Cow Head Group and the Lower Head Formation in places as discussed by Botsford (1988) and by the author in chapter 3. In addition, even the rapid lithofacies change between shales and sandstones may represent an unconformity. The lower part of the formation is characterised by slumping, sliding and sandstone injection, followed by an abrupt change to conglomeratic facies. At Martin Point South, the bedding relationships documented in chapter 3 may also represent a syntectonic angular unconformity.

Despite the evidence of tectonic activity during the deposition of the Lower Head

Formation there is little evidence regarding development of the western margin of the basin, however dolomitic siltstones may be derived from the western margin, and minor recrystallised calcarenites within the formation which appear to be of shallow water origin may indicate sporadic contribution of material from the western margin.

It been noted (chapter 1) that there does not appear to be an equivalent to the Lower Head Formation in the Hare Bay Allochthon. The identification of sandstones similar to those in the Goose Tickle group within the Northwest Arm Formation of the Hare Bay Allochthon raises the question of whether these sands were deposited in another satellite basin, or whether they represent deposition near the bottom of the eastern slope to the main foreland basin.

The fact that the entire Northwest Arm Formation has itself been involved in slumping tends to obscure relationships, and in addition only a thin section through the sequence is exposed. As well, the author did not realise the significance of the unit at the time and did not study the transition in detail. However, the transition from passive margin to active margin sedimentation does seem to be marked by the subsidence typical of the Goose Tickle group, rather than the uplift characteristic of the Lower Head Formation. The sandstone lithologies are also more similar to the American Tickle formation than they are to the Lower Head Formation, although the beds are thicker than those usually found in the American Tickle formation.

Thus it is here suggested that the sandstones in the Northwest Arm Formation do not represent a satellite basin, but instead represent an easterly part of the foreland basin floor which has been uplifted close to a thrust fault. The collection of fossils from these

sandstones should be attempted to try to place constraints on the timing of deposition, and hence the evolution of this most easterly preserved part of the foredeep basin. If this interpretation is correct, the model for the foreland basin in this area would be similar to B (in figure 7.2) in the case of the Hare Bay area and the Northwest Arm Formation, whereas the situation in the Humber Arm Allochthon area would be similar to D.

7.3.3.3 Comparison With Quebec Segment of the Foreland Basin

A comparison of the Lower Head Formation with the Tourelle Formation, which is a similar unit of similar age to the Lower Head Formation in the Quebec Appalachians (Hiscott, 1978) shows that while the Tourelle Formation resembles the Lower Head Formation in many respects, conglomeratic facies are not as abundant, indicating that the basin margin was not cannibalised to the same extent.

The relationship between the Tourelle Formation and the Cloridorme Formation differs in another important way in that there is a much larger time gap between deposition in the Tourelle (Arenig) trench slope basin (Hiscott et al., 1986) and the foredeep basin which is represented by the Cloridorme Formation (Caradoc). The time gap is much less between the Lower Head Formation (Arenig - Llanvirn) and the Goose Tickle Group (Llanvirn - ?Llandeilo).

In addition, the eastern slope to the Newfoundland segment of the foredeep basin appears to have been steeper than that in Quebec, as evidenced by slumping, gravity flows and the absence of megaturbidites.

7.3.3.4 Comparisons With Other Features Observed in Foreland Basins

Ori et al. (1986) have documented complex seismic features in the Apennine basins which they believe represent the products of erosion from structural highs. Although lithological information which supports the information from these seismic features is limited, it is believed they may be characterised by either sandstones and conglomerates, or slumped units. Ori et al. (1986) suggested that sandstones and conglomerates indicate subareal erosion of the thrust front, whereas slumping indicates submarine erosion. They refer to the deposits generated by these processes as 'denudation complexes'. Clearly the Northwest Arm Formation represents such a denudation complex, and it may in fact represent an evolving denudation complex, from conglomerates and shale chip conglomerates of extrabasinal and marginal basin origin, to slump deposits generated in a submarine setting, possibly as sea level rose during the Llanvirn. In addition, the conglomerates of the Lower Head Formation could also be described as such a 'denudation complex' this time derived by subaerial erosion.

Karig et al. (1987) describe similar features in the Timor trough, which, since it involves the flexing of continental crust in response to the collision of the Banda Arc with the Australian continental margin, is considered a good analogue for the Appalachian situation, at least for the earlier phases of the Taconic Orogeny. Slumping in the Timor trough, however, is not related to thrusting, but to normal faulting, which is interpreted as the reactivation of older rift related faults in response to the collision. This raises the possibility that the faults responsible for the cannibalisation of the eastern margin of the Lower Head basin(s) may have been normal faults.

Karig et al. (1987) also noted that the Timor Trough contains a wide variation in sediment thickness, caused by the evolution of laterally discontinuous folds and thrusts. Sediment in the trough is very fine grained clastic and biogenic carbonate sediment, which is interpreted by Karig et al. (1987) to indicate that no submarine canyons supplied sediment to the trough and most of the sediment was trapped in basins in the trench slope area. The lower slope in the area of their survey is underlain by thrust and fold slices of the Australian passive margin sequence, which form linear ridges which can be traced along strike for approximately 30 kilometres. The structural lows between the ridges are trench slope basins, which may have an along strike extent of 30 - 50 km. Karig et al. (1987) did not state the width of these basins, but indicated that spacing between the ridges is variable, and that the entire width of the lower slope is only 20 km. This suggests that these basins are at most only a few km wide.

These features are in good agreement with the structural and sedimentological setting of the finer grained Goose Tickle group (except for the sparsity of sediment in the Timor trough), and the coarser grained Lower Head Formation, which was most likely deposited in a lower slope basin. Karig et al. (1987) also identified an upper slope basin. An upper slope basin may have been present in the Newfoundland foreland basin system which would have facilitated mixing of the sediment that was ultimately supplied to the trench slope basins and foredeep proper (figure 6.13). This aspect is expanded on below.

Another possible analogue is the Taiwan region, in which the Luzon arc has collided with the Chinese passive margin, uplifting the fold and thrust belt which now

constitutes the island of Taiwan (Lundberg and Dorsey, 1988). The most interesting aspect here is the discussion by Lundberg and Dorsey (1988) of a Plio-Pleistocene basin located between the thrust belt and the arc (see figure 6.13). These authors state that it should be expected that linear orogens will shed detritus laterally to both sides into basins deepened by tectonic loading. According to this model, the basin located towards the arc (figure 6.13) (a forearc basin subsequently caught in collision) would receive sediment both from the 'dying arc' and from the uplifted orogen. In the western Newfoundland situation, the 'uplifted orogen' would consist of compressed and uplifted remnants of the passive margin. It may be this type of basin, not preserved in western Newfoundland, which was the locus of sediment deposition prior to transport of detritus into the Newfoundland foreland basin.

Modern analogues within the Taiwan system are available for study because the collisional zone has propagated to the south of Taiwan, and Lundberg and Dorsey (1988) suggested that comparison shows that sedimentation in a forearc basin of this type may vary considerably. At certain times the basin may have contained widespread shallow water deposits, at others, a shallow shelf may not have been well developed and deep water sediments may instead have been deposited. Detritus in the basin includes sedimentary and metasedimentary rock fragments derived from the 'orogen', with subordinate amounts of volcanic and ophiolitic detritus. Transport of detritus from this type of basin into the Newfoundland foreland basin could easily account for both the compositional and textural variability of the detritus in the Newfoundland foreland basin.

A comparison of the Newfoundland foreland basin with the main foredeep basin (see figure 6.13) in the Taiwan orogen shows considerable similarity between the two, but a notable difference between the Taiwan system and the Appalachian basin in western Newfoundland is that sandstone composition in both Taiwan basins documents progressive unroofing of the orogen (Dorsey, 1988). This has not been documented by the author for the foreland basin in western Newfoundland, nor has such a relationship been observed by other workers in the Canadian Appalachians (e.g. Ko, 1985), and generally in foreland basins it appears to be uncommon (Schwab, 1986).

Metamorphic fragments in the Newfoundland examples are less abundant than reported by Dorsey (1988), although it is possible that potassium feldspar in western Newfoundland sandstones originated at a hitherto unidentified metamorphic source.

The recent reinterpretation by Jenner et al. (1991) and Elton (1991) of the Bay of Islands ophiolite may have a bearing on this aspect of the discussion. If the Bay of Islands Ophiolite was formed in a back arc basin, this necessarily implies the existence of an arc, which, if the subduction zone was dipping east, would have been located to the east of the foreland basin (and west of the back arc basin - see figure 6.13). Thus a forearc basin may have existed to the east of the foreland basin, and may have received sediment from both the arc and uplifted remnants of the ancient passive continental margin producing a situation analogous to the one described by Lundberg and Dorsey (1988). This sediment may subsequently have been funneled into the foreland area via structural irregularities in the uplifted area. The area of mixing of sediment could also have included a high trench slope basin or system of basins, which have subsequently

been overriden by the orogen, or which were themselves uplifted and eroded.

7.3.3.5 Synthesis

The fundamental characteristics of the western Newfoundland foreland basin system (see figures 6.13 and 7.1) which can be derived from the discussions in this chapter are:

1. A long narrow, confined, foredeep basin;

2. A relatively steep slope on the eastern margin of the basin (as compared with Quebec examples);

3. At least three sediment input points to the basin;

4. Agreement of positioning of sediment input points with independently inferred structural discontinuities;

5. Deposition of granule conglomerates, pebble-cobble conglomerates and olistrostromes related to faulting in advance of allochthon emplacement;

6. Presence of slightly older satellite basins fed by sandy fans and bounded by faults;

7. Syndepositional tectonic activity within both satellite and main foreland basins;

8. Lobe switching and reactivation of rift-related faults in the Mainland Area;

9. Probability of major system of basins on the east side of the foreland basin in which mixing of detritus took place;

10. Supply of sediment from a major and complex area of uplift which included passive margin sediments, possibly Grenville basement, and a major arc terrane which was under compression.

7.4 FUTURE WORK

This project has provided a reconnaissance-style overview of foredeep basin and related sandstones in western Newfoundland. Many problems remain to be solved. This study, for example, has not involved a detailed statistical petrographic comparison between localities within units, which might have separated local source areas from regionally mixed sediment supply in the manner outlined by Ingersoll (1990). Nor has a study to investigate petrographic variation through time been attempted (e.g. Dorsey, 1988).

A more rigorous attempt might have been made to relate geochemistry to modal composition, but this would likely have involved restriction of the grain sizes considered, and would have obscured some of the important relationships indicated by the variation in the geochemical parameter al-alk.

A study of the diagenetic behaviour of serpentine in these rocks would be of considerable interest, as would a varietal study of heavy minerals in relation to modal composition such as that carried out by Thornburg and Kulm (1986). A study of this type might also allow for an investigation into the relationship between chromite abundances and detrital chloritised serpentine, to shed further light on the behaviour of Cr and Ni in these sediments.

The method of bulk analysis of volcanic fragments by electron microprobe, may have some useful applications in more closely characterising volcanic source areas, particularly in the Lower Head Formation. Dating of individual zircon grains may also provide clues as to the ages of the sources. The most crucial grains to be dated are

feldspars, in particular rounded microcline, in order to reduce the number of hypotheses for their origin.

One of the most pressing requirements for further advancement in knowledge regarding the units investigated in this study is the collection of new paleontological sites, and the recollection of existing sites, to place better time constraints on the events outlined in this thesis.

The author plans to pursue many of these aspects as part of her future research career. Despite the shortcomings necessarily involved in such a wide ranging study, the author believes that this thesis represents a significant contribution to the geology of western Newfoundland such that the hypotheses presented here may be tested using some of the approaches outlined above.

The main contributions of this thesis have included:

1. Placement of foreland basin sandstone units in a stratigraphic framework;

2. Description, interpretation and basin-wide analysis of their sedimentological characteristics;

3. A qualitative and quantitative characterisation of their petrography which did not previously exist;

4. A qualitative and quantitative characterisation of their geochemistry which did not previously exist;

5. An investigation into various methodologies for interpretation of geochemical data for sandstones;

6. An evaluation of provenance of western Newfoundland foreland basin sandstone units

in light of geochemical and petrographic data from older sedimentary rocks whose equivalents may have acted as sources, and for which information was previously sparse or non-existent;

7. Integration of all of the above into a current model for the tectonic evolution of the western Newfoundland foreland basin.

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Williams, H., and Stevens, R.K., 1974: The ancient continental margin of eastern North America. In Burke, C.A., and Drake, C.L., (eds.), the Geology of continental margins. Springer-Verlag, New York, p. 781-796.

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Williams, S.H., Boyce, W.D., and James, N.P., 1987: Graptolites from the Middle Ordovician St. George and Table Head Groups, western Newfoundland, and implications for the correlation of trilobite, brachiopod, and conodont zones. Canadian Journal of Earth Sciences, v. 24, p. 456-470.

Williams, S.H., and Stevens, R.K., 1988: Early Ordovician (Arenig) graptolites of the Cow Head Group, western Newfoundland, Canada. Paleontographics Canadiana, vol. 5, p. 1-167.

Wilson, J.T., 1966: Did the Atlantic close and then reopen? Nature, v. 211, p. 676-681.

Winkler, H.G.F., 1979: Petrogenesis of metamorphic rocks. Springer-Verlag, New York, 348 pp.

Young, S.W., 1976: Petrographic textures of detrital polycrystalline quartz as an aid to interpreting crystalline source rocks. Journal of Sedimentary Petrology, v. 46, pp. 595-603.

Zuffa, G.G., 1985: Optical analysis of arenites: influence of methodology on compositional results. In (ed.) G.G. Zuffa, Provenance of Arenites, D. Reidel, Boston, p. 165-189.

Zuffa, G.G., 1987: Unravelling hinterland and offshore paleogeography from deep-water arenites. In (eds.) J.K. Leggett and G.G. Zuffa, Marine Clastic Sedimentology, Graham and Trotman, p. 39-61.

Zuffa, G.G., 1991: On the use of turbidite arenites in provenance studies: critical remarks. In (eds.) A.C. Morton, S.P. Todd, and P.D.W. Haughton, Developments in Sedimentary Provenance Studies, Geological Society Special Publication, no. 57, p. 23-29.

APPENDIX 1

SECTION A1.1: LIST OF LOCATION ABBREVIATIONS

ABBREVIATION	LOCATION	FORMATION
BA	Bakeapple Is. (4)	American Tickle
BB	Bellburns (3)	American Tickle
BBN	Black Brk. N. (2)	Lower Head
BI	Raleigh (4)	American Tickle
BMD	Blow me Down Brk. (2)	Blow me Down
BP	Black Point (2)	Lower Head
BURNT	Burnt Island (4)	American Tickle
CB	Clam Bank (1)	Clam Bank
CBB	Crabbe Brook (2)	Crabbe Brook
CR	Cow Rocks (1)	Long Point Gp.
DB	Degras (1)	Hawke's Bay
EI	Eagle Island (2)	Lower Head
E-WP	White Point (2)	Irishtown
GM	Gros Morne (3)	Hawke's Bay
GT	Goose Tickle (4)	American Tickle
HAN	Humber Arm North (2)	Summerside
IRI	Irishtown (2)	Irishtown
LHN	Lower Head North (3)	Lower Head
LHS	Lower Head South (3)	Lower Head
LP	Low Point (1)	Mainland
LSI	Little Springs In. (4)	American Tickle
MAID	Maiden Point (4)	Maiden Point
MAP	Middle Arm Point (2)	Lower Head
ML	Mainland (1)	Mainland
MPN	Martin Point N. (3)	Lower Head
MPS	Martin Point S.(3)	Lower Head
MP	Maiden Point (4)	Lower Head
NWA	Northwest Arm (4)	Northwest Arm
PCF	Portland Crk. Feeder(2)	Lower Head
PCP	Portland Crk. Pond (2)	Lower Head
PP	Parsons Pond (2)	American Tickle
PORT	Portland Crk. (2)	Lower Head
RPA	Rocky Point (1)	Lower Head
SAINT	Mt. St. Margaret (-)	Bradore
SB	Shallow Bay (4)	American Tickle
SAB	Shallow Bay (4)	American Tickle
SAB 3	Saint Anthony Bight (4)	Maiden Point
SPI	St. Paul's Inlet (3)	American Tickle

TC	Table Cove (3)	American Tickle
TRC	Three Rock Cove (1)	Mainland
TP	Triangle Point (4)	Northwest Arm
WBN	Western Brook Pond N.(2)	Lower Head
WBS	Western Brook Pond S.(2)	Lower Head
WH	Winterhouse (1)	Winterhouse
WI	Woods Island (2)	Blow me Down
WF	Fox Island River (-)	Blow me Down

(Note: numbers in brackets indicate location map. Not all of the individual localities are marked on location maps. Individual locations are given in the following list)

A1.1.1 GRID REFERENCES FOR SAMPLES

119-86-2		NTS 12H/12 VE 352832
BA	3	NTS 2M/12 WH 800158
BA	4	"
BB	B2	NTS 12I/6 & 12I/5 VF 600706
BB	B4	"
BB	B9	"
BBN	1	NTS 12G/1E VE 163401
BI	B3	NTS 2M/12 WH 882133
BMD	2	NTS 12G/1E VE 097351
BMD	5	NTS 12G/1E VE 103351
BMD	7	NTS 12G/1E VE 133348
BMD	8	NTS 12G/1E VE 128349
BP	3	NTS 12B/10 UD 756846
BP	7	"
BP	10	"
BURNT	2	NTS 2M/12 WH 863117
CB	9	NTS 12B/11 UD 528910
CB	10	"
CB	11	"
CB	B1	NTS 12G/1E VE 176533
CR	B2	NTS 12B/11 UD 395833
CROQ	6	NTS 2M/4 WG 877619
DB	4	NTS 12B/6 UD 406728
DB	9	"
E-WP		NTS 12G/1E VE 230406
EI	2	NTS 12G/1E VE 163463
EI	4	"
EI	6	"

GM	1	NTS 12H/12 Ve 426932
GM	3	"
GT	1	NTS 12P/8 WG 675823 south to 12P/1 WG 672776
GT	B5	"
GT	B10	"
HAN	B5	NTS 12A/13 VE 288249
HAN	B7	NTS 12G/1E VE 185347 section north to 179358
HAN	B12	"
HAS	B6	NTS 12G/1E VE 166303
HB	1	NTS 12I/11 VG 867054
HB	6	NTS 12I/11 VG 832048
IRI	1	NTS 12G/1E VE 176287
IRI	3	"
LHN	B4	NTS 12H/13 446353
LHN	B6	"
LHS	B2	NTS 12H/13 448343
LHS	B5	"
LHS	B6	"
LHS	B8	"
LHS	B10	"
LHS	B12	"
LP	B1	NTS 12B/11 402833
LQ-82-163		NTS 12H/5 VE 390763
LQ-83-51		NTS 12H/5 VE 409731
LSI	1	NTS 2M/4 WG 815737
LSI	5	"
MAID	1	NTS 2M/4 WG 834739
MAP	B1	NTS 12G/1E VE 163427
MAP	B3	"
MAP	B7	"
MAP	B10	"

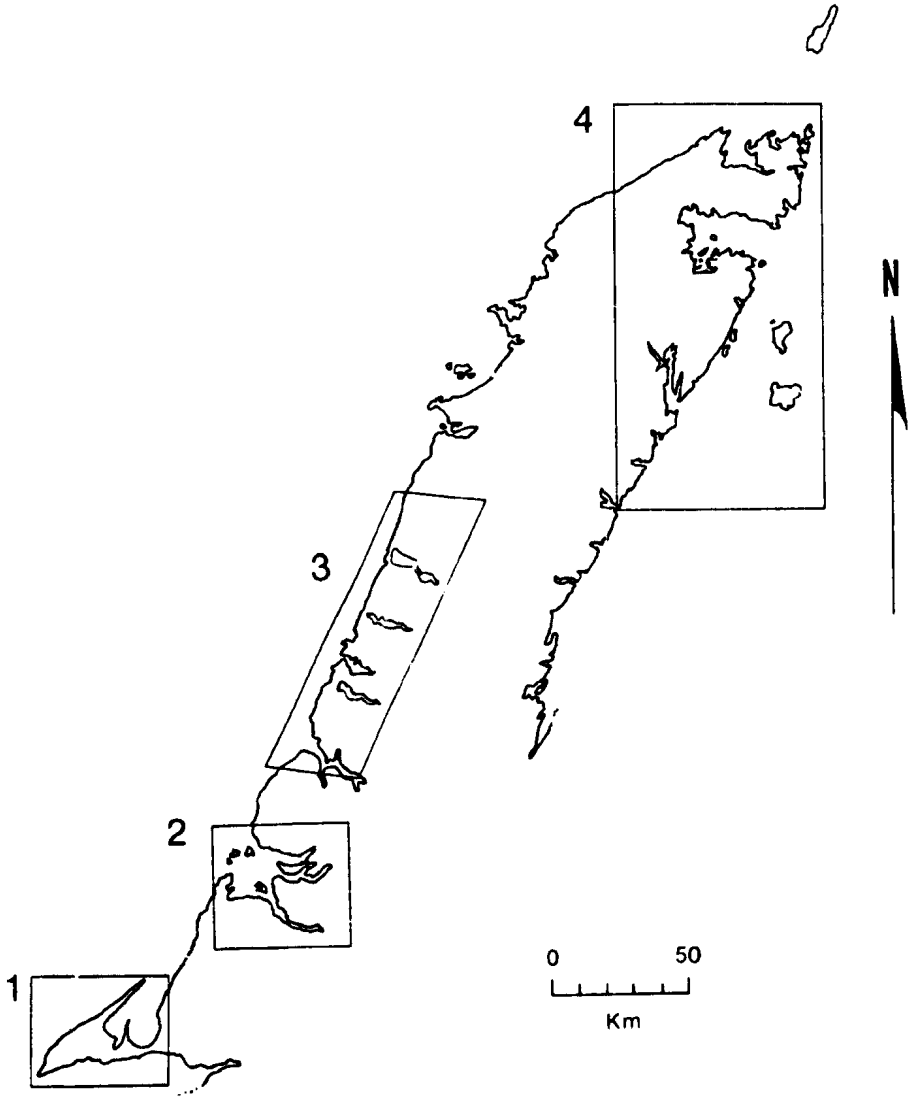
ML	4	NTS 12B/11 UD 386 north to 393818
ML	8	"
ML	11	"
ML	12	"
ML	15	"
ML	20	"
ML	21	"
ML	22	"
ML	23	"
ML	24	"
ML	25	"
ML	26	"
ML	A10	"
ML	A14	"
ML	B7	"
ML	B8	"
ML	B9	"
MP	B1	NTS 2M/5 & 2M/6 WG 988903
MP	B5	NTS 2M/5 & 2M/6 WG 982947
MPN	5A	NTS 12H/13 VF 341124
MPN	5B	"
MPN	7B	"
MPN	8	"
MPN	12	"
MPS	11	NTS 12H/13 VF 341124
MPS	13	"
MPS	23	"
N 239 G		Bradore Formation, Labrador, no location available
NWA	10	NTS 12P/8 WG 663898
NWA	12	"
PCF	1	400m N of mouth of Portland Creek Feeder, no location available.
PCF	2	"
PCF	4	"
PCI	1	NTS 12I/4 VF 607607
PCI	2	"
PCP	B1	NTS 12I/4 VF 645622

PH	4	NTS 12I/4 VF 556550
PORT	1	NTS 12I/4 VF 537546
PORT	2	NTS 12I/4 VF 536544
PORT	B2	"
PP	B1	NTS 12H/13 VF 570321
RPA	2	NTS 12B/10 VF 554898 north to 562908
RPA	5	"
RPA	10	"
RPA	11	"
RPA	14	"
SAB	1	NTS 2M/5 & M/6 XG 011930
SAB	3	"
SAB	9	NTS 2M/12 WH 780082
SAB	10	"
SAINT	1	3 km S of Mt. St. Margaret microwave tower 197 on access road, no grid reference available.
SB	2	NTS 2M/12 WH 780083
SB	8	"
SB	B3	"
SB	B2	"
SPI	B1	NTS 12H/13 VF 518215
TC	3	NTS 12I/6 & 12I/5 VF 619779
TC	4	"
TC	6	"
TC	7	"
TC	A3	"
TC	A6	"
TC	A12	"
TC	A16	"
TP	5	NTS 2M/12 WH 818072
TP	B3	NTS 2M/5 & 2M/6 WH 820054
TP	B7	NTS 2M/12 WH 818072
TRC	1	NTS 12B/11 UD 420851 south to 408837
TRC	3	"

TRC	4	"
TRC	5	"
TRC	7	"
TRC	A1	"
TRC	A5	"
TRC	A7	"
TRC	A10	"
TRC	A13	"
TRC	A16	"
TRC	A20	"
TRC	A21	"
TRC	A25	"
TRC	A28	"
WBN	3	NTS 12H/13 VF 402153 to 413152
WBN	6	"
WBN	A3	"
WBN	A15	"
WBS	1	NTS 12H/13 VF 395147 to 394144
WBS	9	"
WBS	B1	"
WBS	B2	"
WF-75-85		Blow me Down Brook Formation north of Fox Island River, no location available
WF-76-85		"
WH	1	NTS 12B/10 UD 626979
WI	B2	NTS 12G/1E VE 105387
WI	B3	"

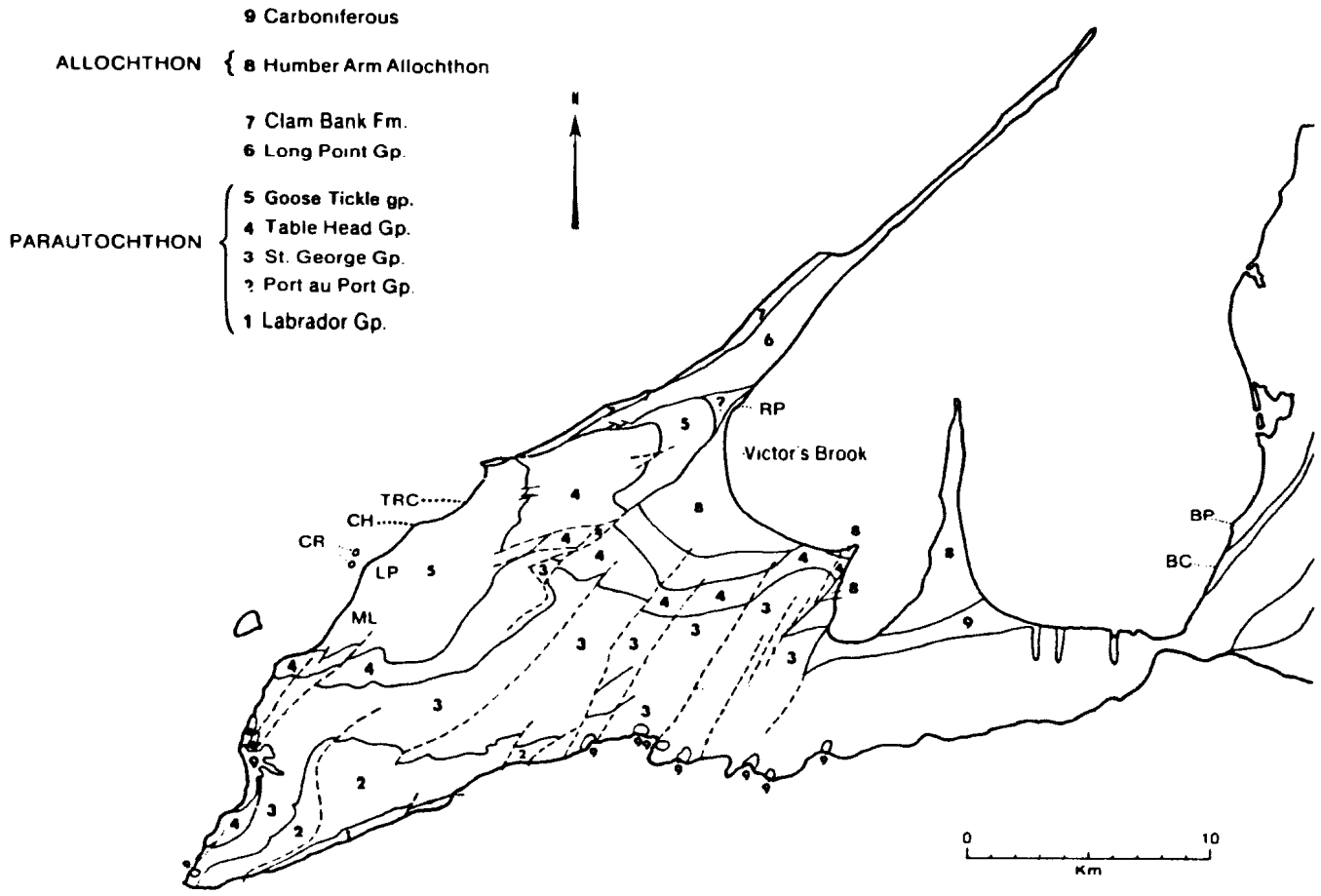
SECTION A1.2 GENERAL LOCATION MAP

General location map showing key to detailed location maps.
1 = Port au Port Peninsula. 2 = Bay of Islands area. 3 = area north of Bonne Bay.
4 = Pistolet Bay and Hare Bay areas.


4
3
2
1
N
0
50
Km

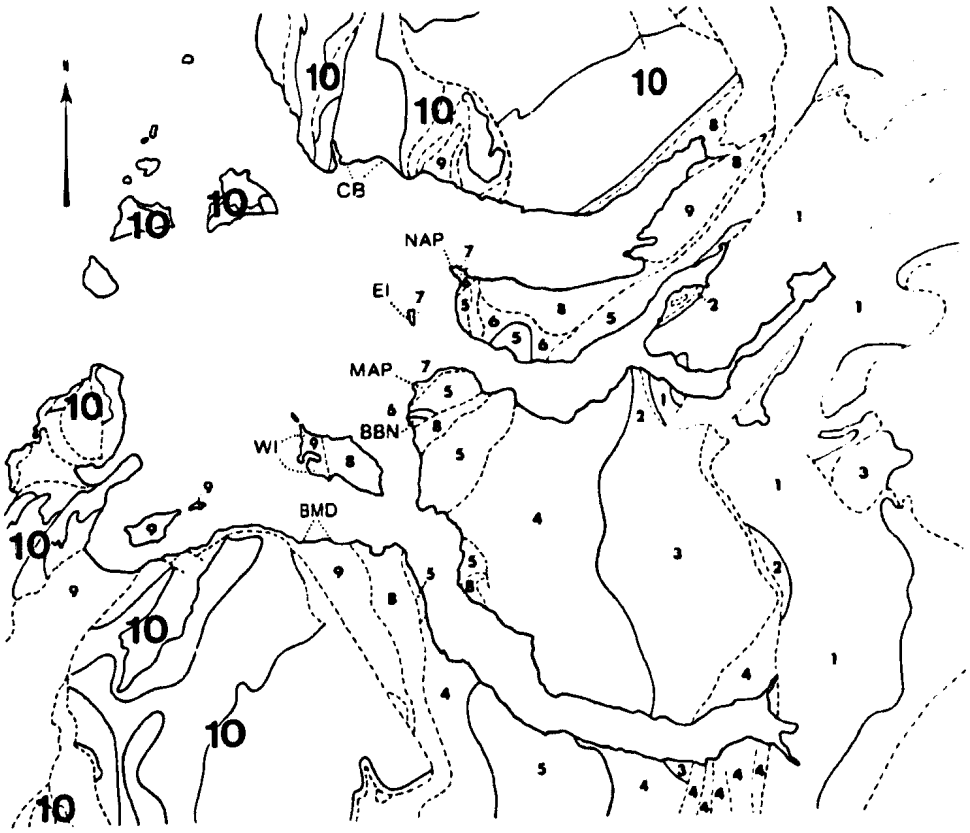
SECTION A1.3 LOCATION MAP 1 PORT AU PORT PENINSULA

Dashed lines=faults. Solid lines=stratigraphic boundaries. ML=Mainland. CR=Cow Rocks. LP=Low Point. TRC=Three Rock Cove. RP=Rocky Point. BC=Black Cove. BP=Black Point. CH=Crow Head. Note that the 'Three Rock Cove Section' is measured from Crow Head south, although folded Mainland formation is also exposed from Three Rock Cove to Crow Head. Note also that the Mainland formation is restricted to the west coast of the Port au Port Peninsula. Map after Williams (1985) and Waldron and Stockmal, 1991).


9 Carboniferous
ALLOCHTHON
8 Humber Arm Allochthon
7 Clam Bank Fm.
6 Long Point Gp.
PARAUTOCHTHON
5 Goose Tickle gp.
4 Table Head Gp.
3 St. George Gp.
2 Port au Port Gp.
1 Labrador Gp.
N
RP
Victor's Brook
TRC
CH
CR
LP
ML
BP
BC
0
10
Km

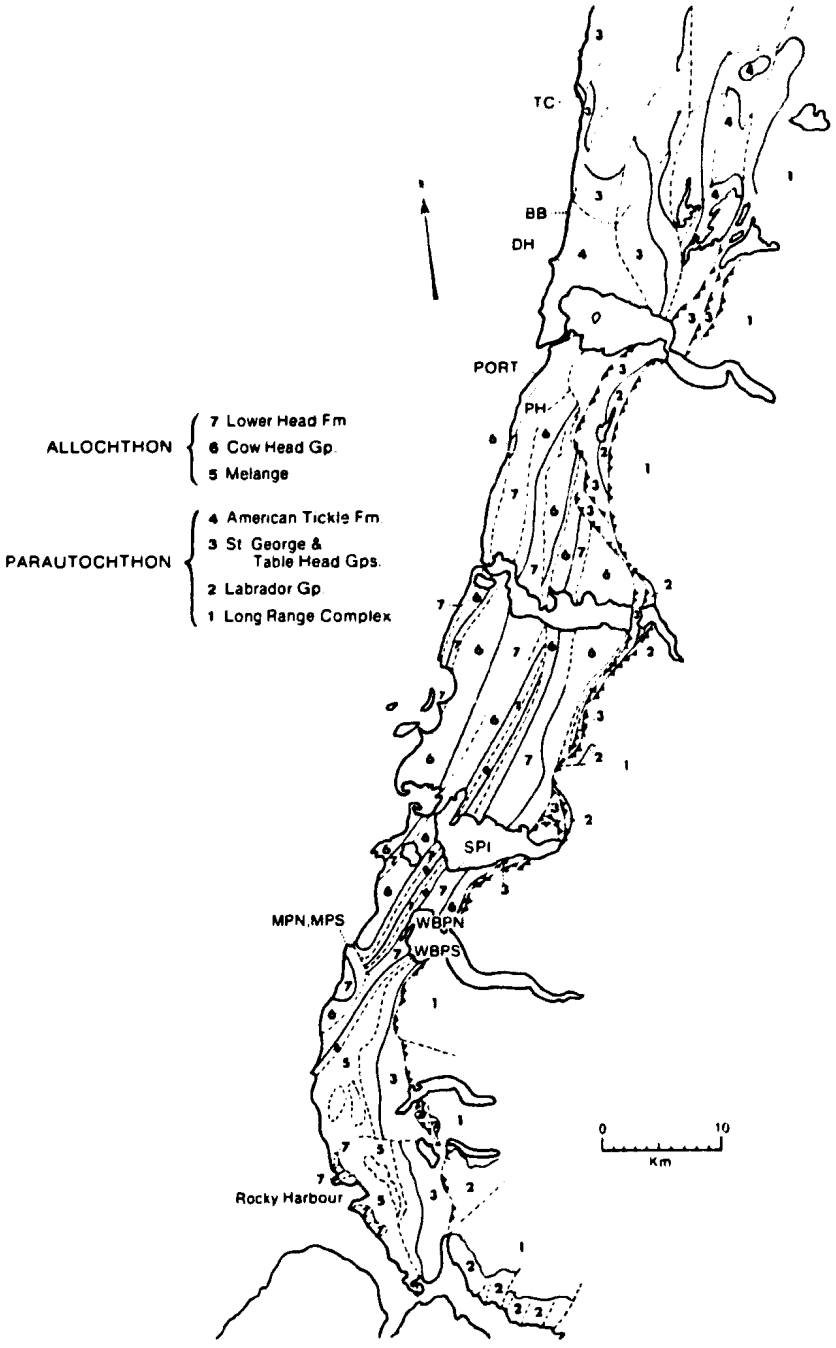
SECTION A1.4 LOCATION MAP 2 BAY OF ISLANDS

Dashed lines=faults. Dotted lines=stratigraphic boundaries. BMD=Blow me Down. WI=Woods Island. MAP=Middle Arm Point. EI=Eagle Island. NAP=North Arm Point. CB=Crabbe Brook. BBN=Black Brook North. Map after Williams and Cawood (1988).


10
CB
NAP
EI
MAP
BBN
WI
BMD
0
10
Km
HUMBER ARM ALLOCHTHON
10 Ophiolitic & Volcanic Rocks
9 Blow Me Down Brook Fm.
8 Melange
7 Lower Head Fm.
6 Middle Arm Point Fm.
5 Cook's Brook Fm.
4 Irishtown Fm.
3 Summerside Fm.
PARAUTOCHTHON
2 American Tickle Fm.
1 Cambrian Ordovician Carbonates

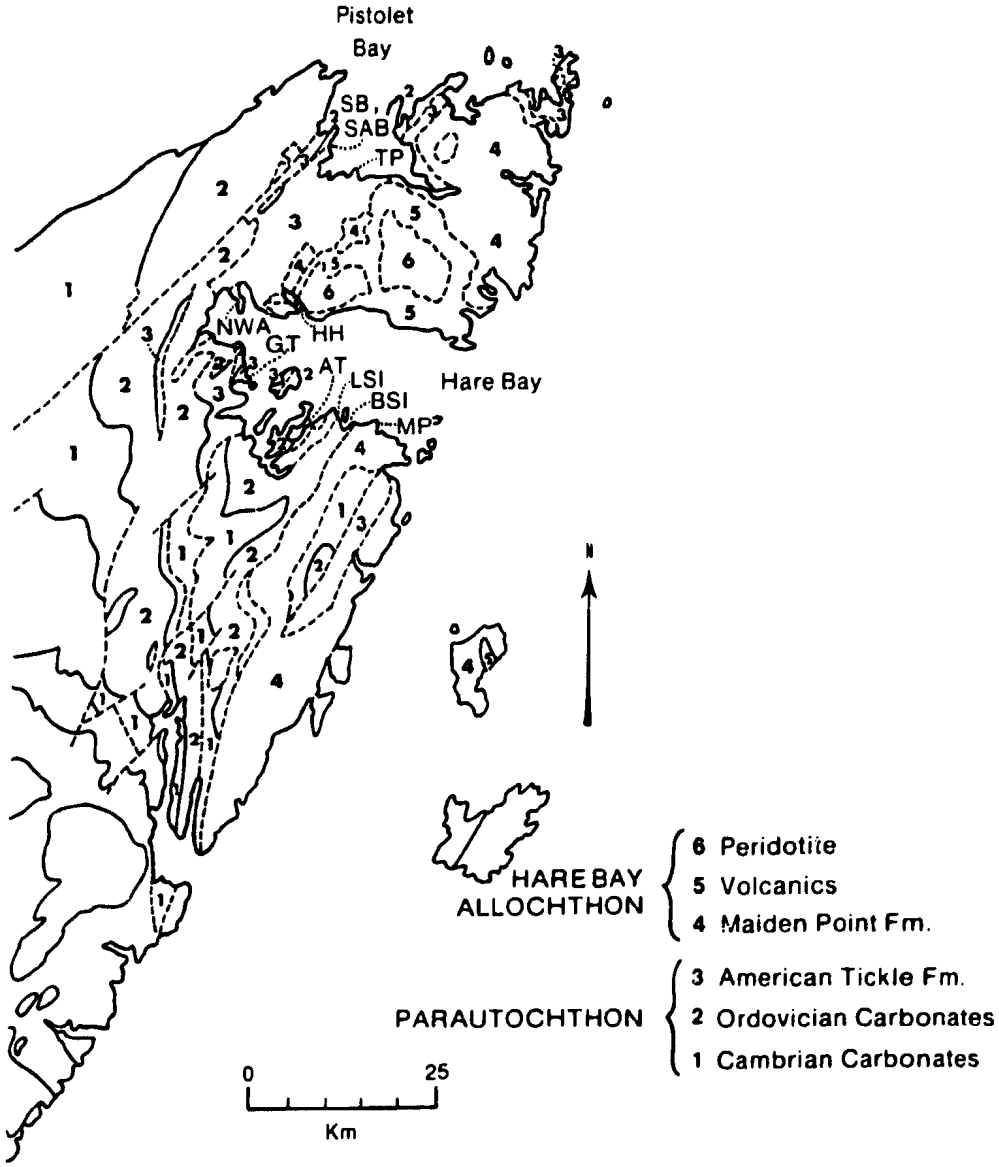
SECTION A1.5 LOCATION MAP 3 NORTH OF BONNE BAY

Dashed lines=faults. Solid lines=stratigraphic boundaries. Toothed lines=major thrust faults. MPN=Martin Point North. MPS=Martin Point South. WBPN=Western Brook Pond North. WBPS=Western Brook Pond South. SPI=St. Paul's Inlet. PORT=Portland Creek. PH=Portland Hill. DH=Daniel's Harbour. BB=Bellburns. TC=Table Cove. Map after Williams and Cawood (1988)


ALLOCHTHON
7 Lower Head Fm
6 Cow Head Gp.
5 Melange
PARAUTOCHTHON
4 American Tickle Fm.
3 St. George & Table Head Gps.
2 Labrador Gp.
1 Long Range Complex
TC
BB
DH
PORT
PH
SPI
MPN,MPS
WBPN
WBPS
Rocky Harbour
0
10
Km

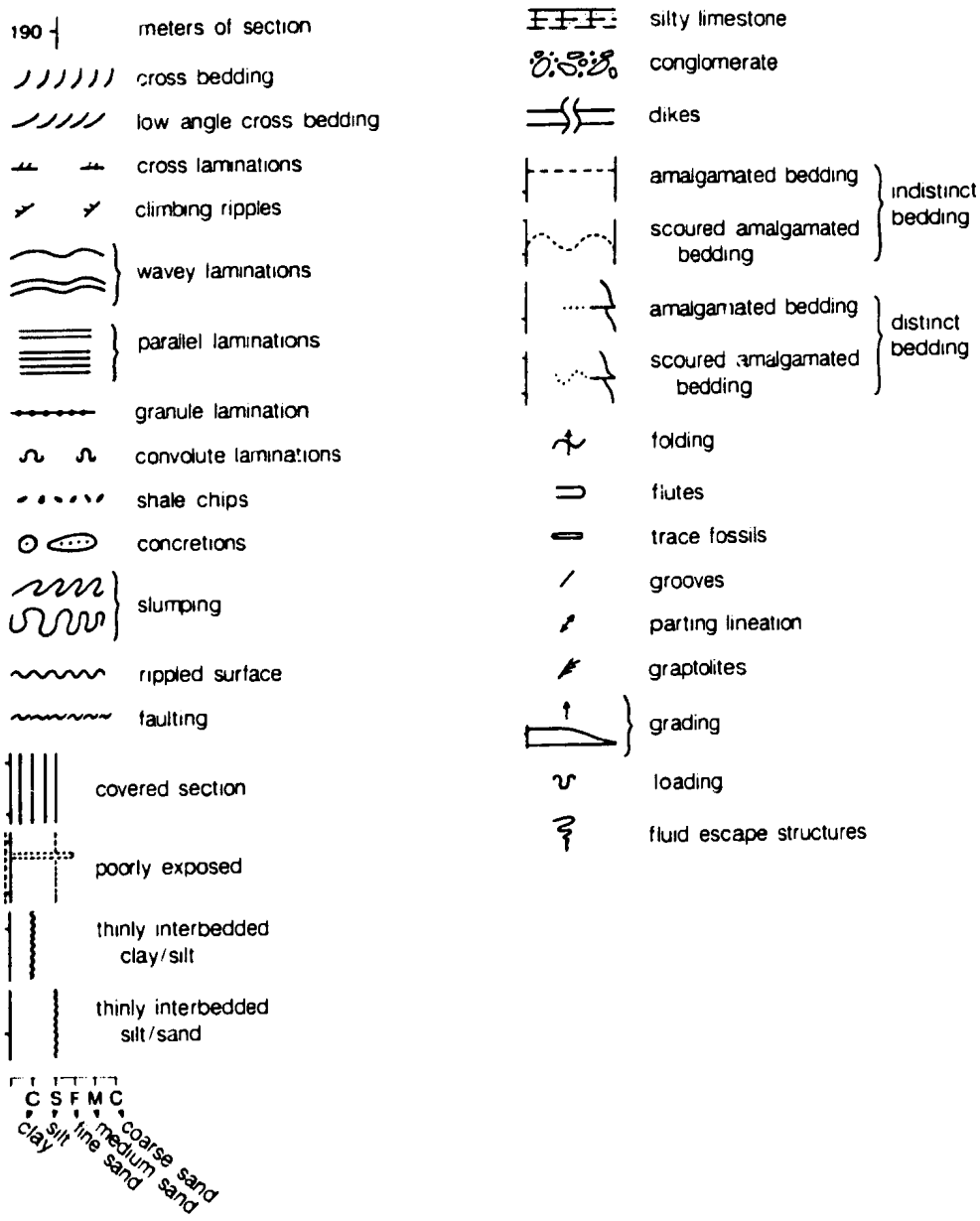
SECTION A1.6 LOCATION MAP 4 HARE BAY AND PISTOLET BAY

Dashed lines=faults. Solid lines=stratigraphic contacts. SB, SAB=Shallow Bay. TP=Triangle Point. NWA=Northwest Arm. GT=Goose Tickle. HH=Howe Harbour. AT=American Tickle. BSI=Big Springs Inlet. LSI=Little Springs Inlet. MP=Maiden Point. Map after Williams and Smyth (1983).


Pistolet
Bay
SB
SAB
TP
NWA
G.T
HH
AT
LSI
BSI
MP
Hare Bay
N
HARE BAY
ALLOCHTHON
6 Peridotite
5 Volcanics
4 Maiden Point Fm.
PARAUTOCHTHON
3 American Tickle Fm.
2 Ordovician Carbonates
1 Cambrian Carbonates
0
25
Km

APPENDIX 2: LOCALITY DESCRIPTIONS AND MEASURED SECTIONS

LEGEND - STRATIGRAPHIC SECTIONS



SECTION A2.1 AMERICAN TICKLE FORMATION

A2.1.1 Goose Tickle

Grid Reference: NTS 12P/8 WG 675823 south to 12P/1 WG 672776.

Exposure: Coastal, intertidal zone, low lying, very poorly exposed near the top.

Structure: Almost flat lying, cleaved in places, folded about axes plunging shallowly SW.

Underlying unit: Black Cove Formation with scattered limestone nodules. Gradational contact. Base of the section taken at the first prominent sandstone unit.

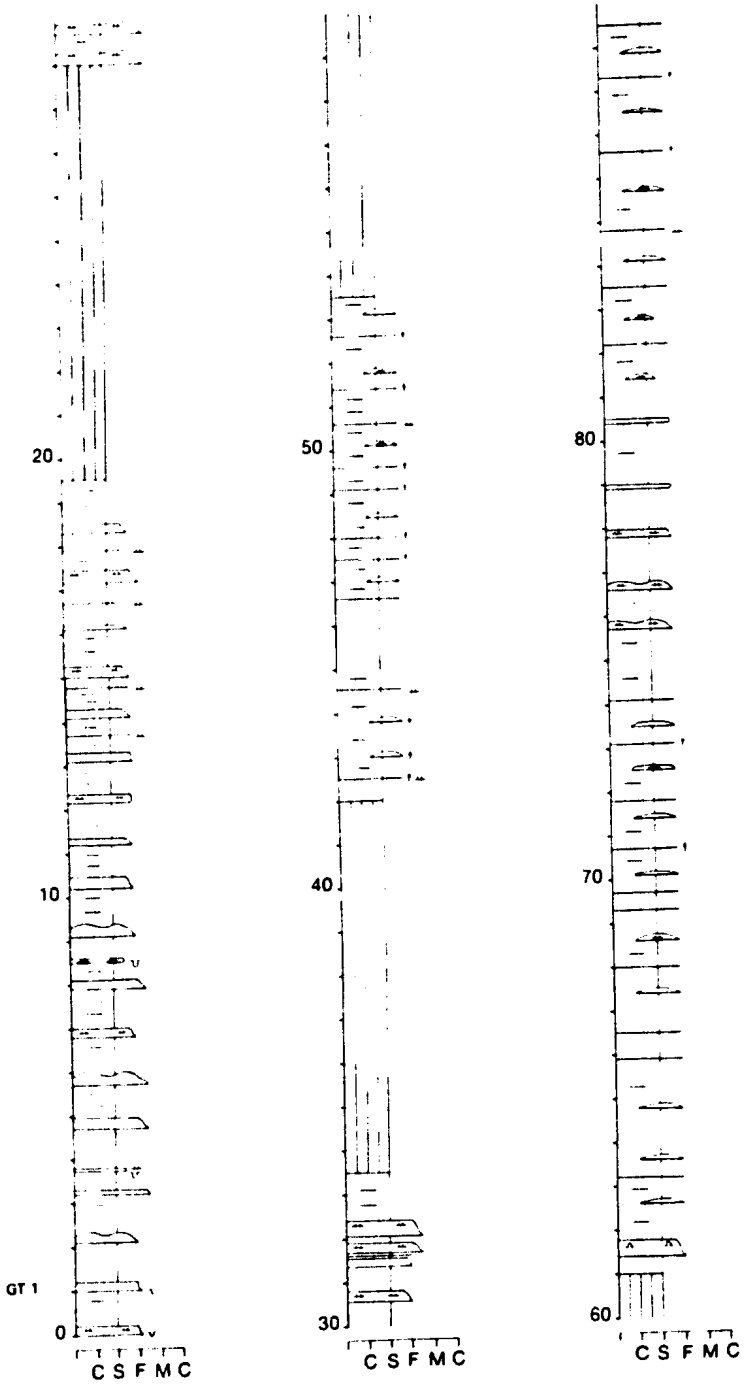
Overlying unit: Northwest Arm Formation. Contact not exposed.

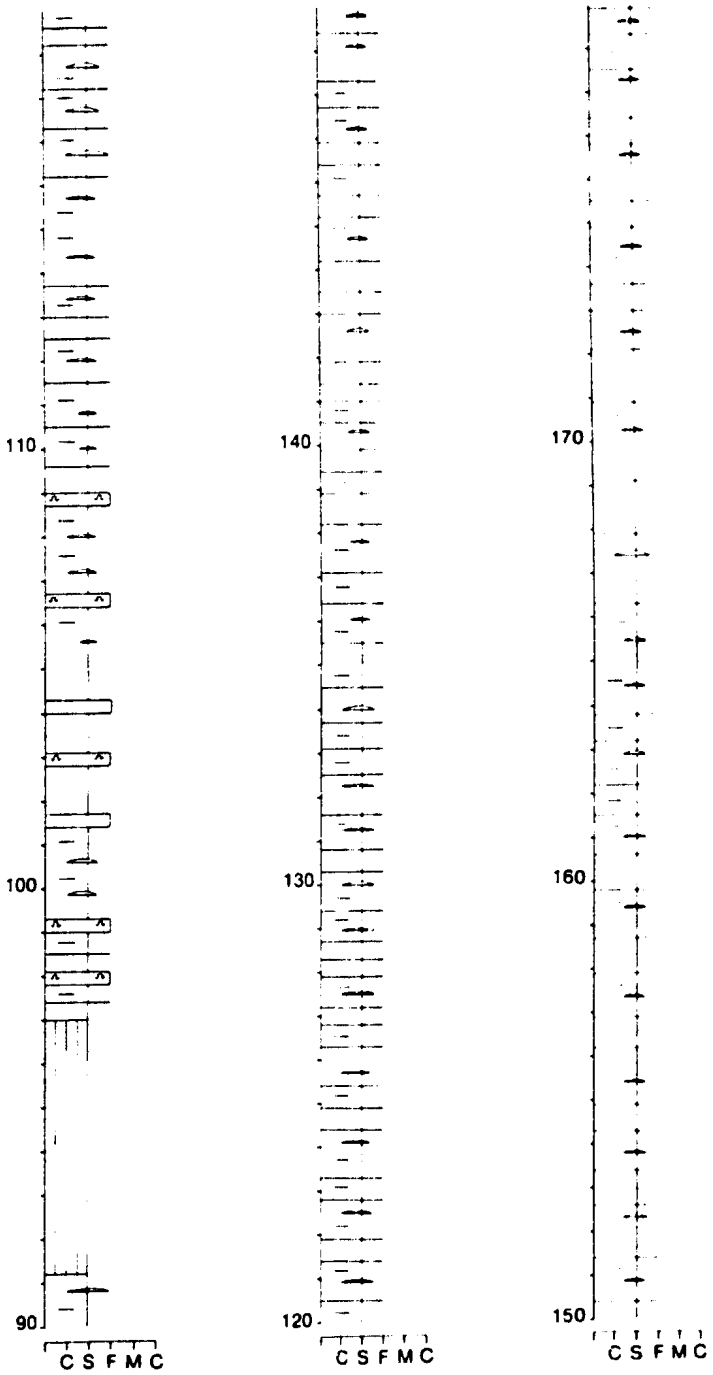
Other comments: The structure of the top of the section is not clear, as only the two conglomerates (which are assigned to the Howe Harbour member) are exposed. The inferred thicknesses between the two conglomerates are an estimate only, as structural interpretations differ (see e.g. Williams and Smyth, 1983; Stouge, 1986). This is the type section for the American Tickle Formation.

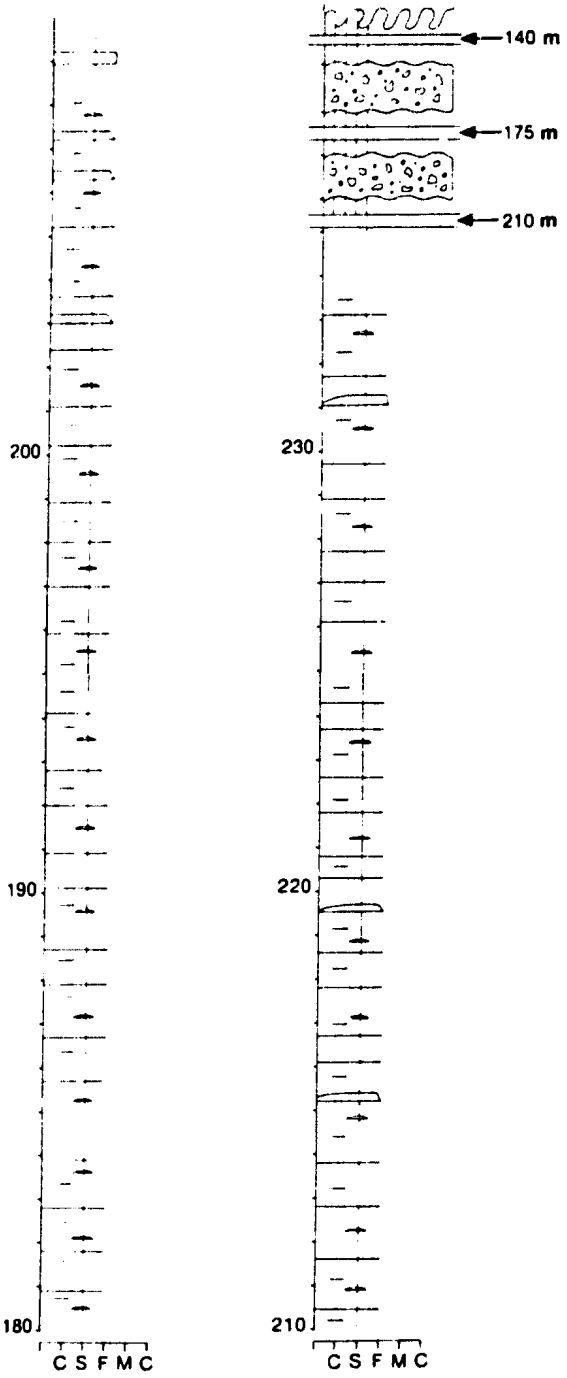
Paleocurrent data:

Ripples

N=13


GT 1
0
10
20
30
40
50
60
70
80
C S F M C
C S F M C
C S F M C


110
100
90
C S F M C
140
130
120
C S F M C
170
160
150
C S F M C


140 m
175 m
210 m
200
190
180
230
220
210
C S F M C
C S F M C

A2.1.2 Shallow Bay

Grid Reference: NTS 2M/12 WH 780083.

Exposure: Low lying coastal exposure, mostly intertidal.

Structure: Fairly simple. Folded along shallowly SW plunging axes.

Underlying unit: Black Cove Formation, gradational contact. Base of the section taken at first prominent sandstone bed.

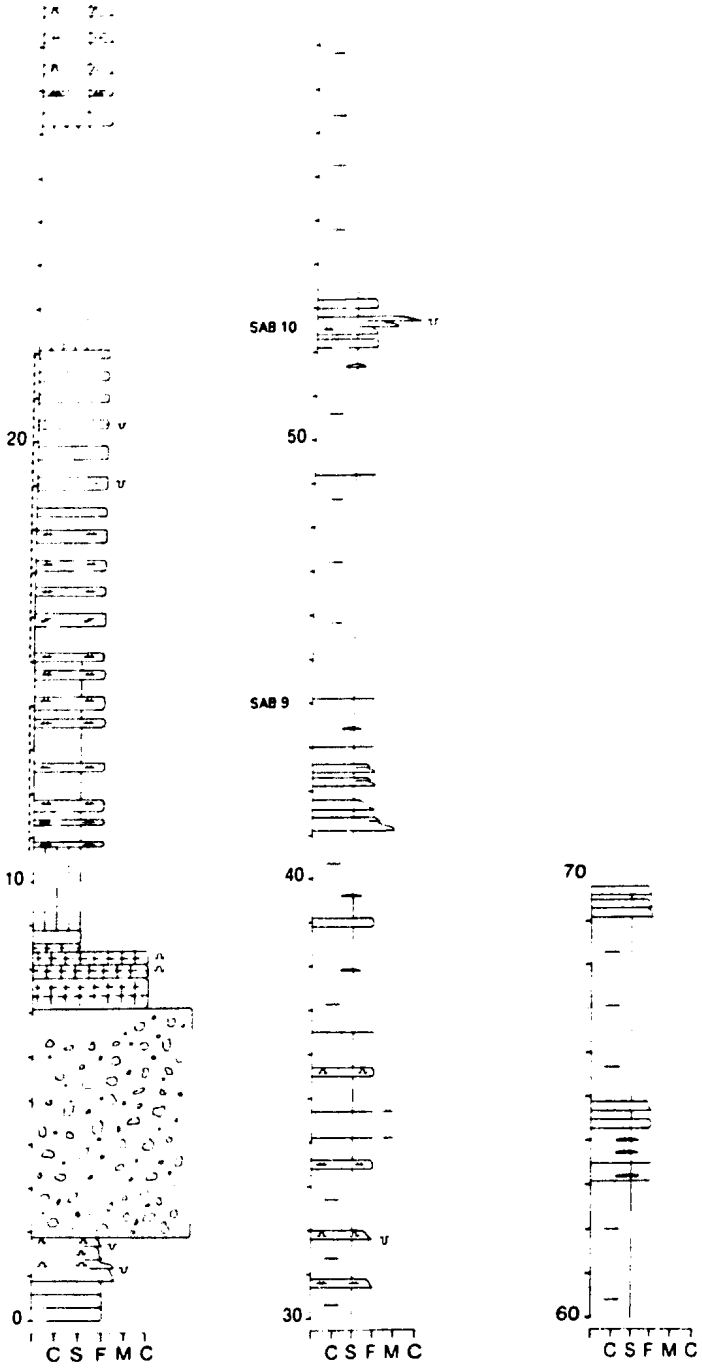
Overlying unit: Top not exposed.

Other comments: This is one of the sections which contains the Daniel's Harbour Member (conglomeratic member near the base of the section).

Paleocurrent data:

Ripples

N=5


SAB 10
SAB 9
0
10
20
30
40
50
60
70
C S F M C
C S F M C
C S F M C

A2.1.3 Table Cove

Grid Reference: 12I/6 & 12I/5 Vf 619779

Exposure: Low lying coastal exposure, intertidal (access only at low tide).

Structure: Simple.

Underlying unit: Black Cove Formation, gradational contact. Base of the section taken at the first prominent sandstone bed.

Overlying unit: Top not exposed.

Other comments: This is a reference section for the American Tickle formation, as it best represents the more sand rich examples of the unit.

Paleocurrent data:

Cross Beds

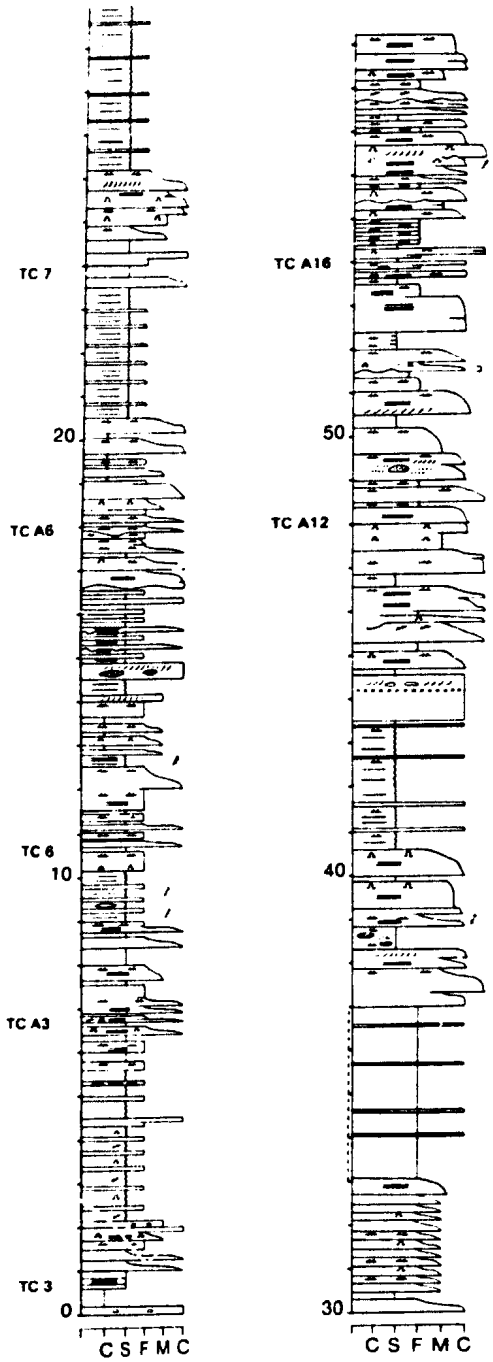
N=13

Parting Lineation

N=2

Ripples

N=62


TC 7
20
TC A6
TC 6
10
TC A3
TC 3
0
C S F M C
TC A16
50
TC A12
40
30
C S F M C

A2.1.5 Bellburns

Grid Reference: NTS 12I/6 and 12I/5 VF 600706

Exposure: Low lying coastal exposure. Intertidal zone, accessible at low tide only.

Structure: Simple, some shallowly southwest plunging folds.

Underlying unit: Black Cove Formation, gradational contact. In this section, the base of the section is the top of the Table Cove Formation and the entire Black Cove Formation is included in the section.

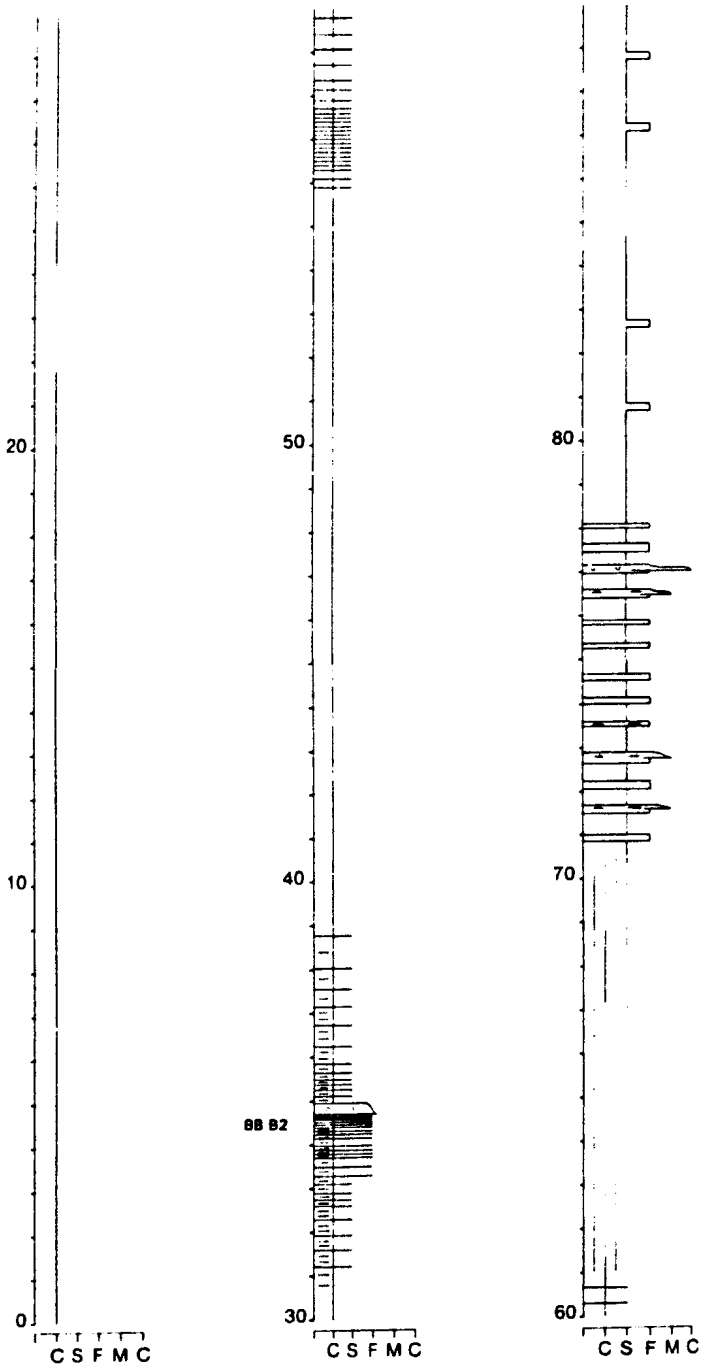
Overlying unit: The top of the unit is not exposed.

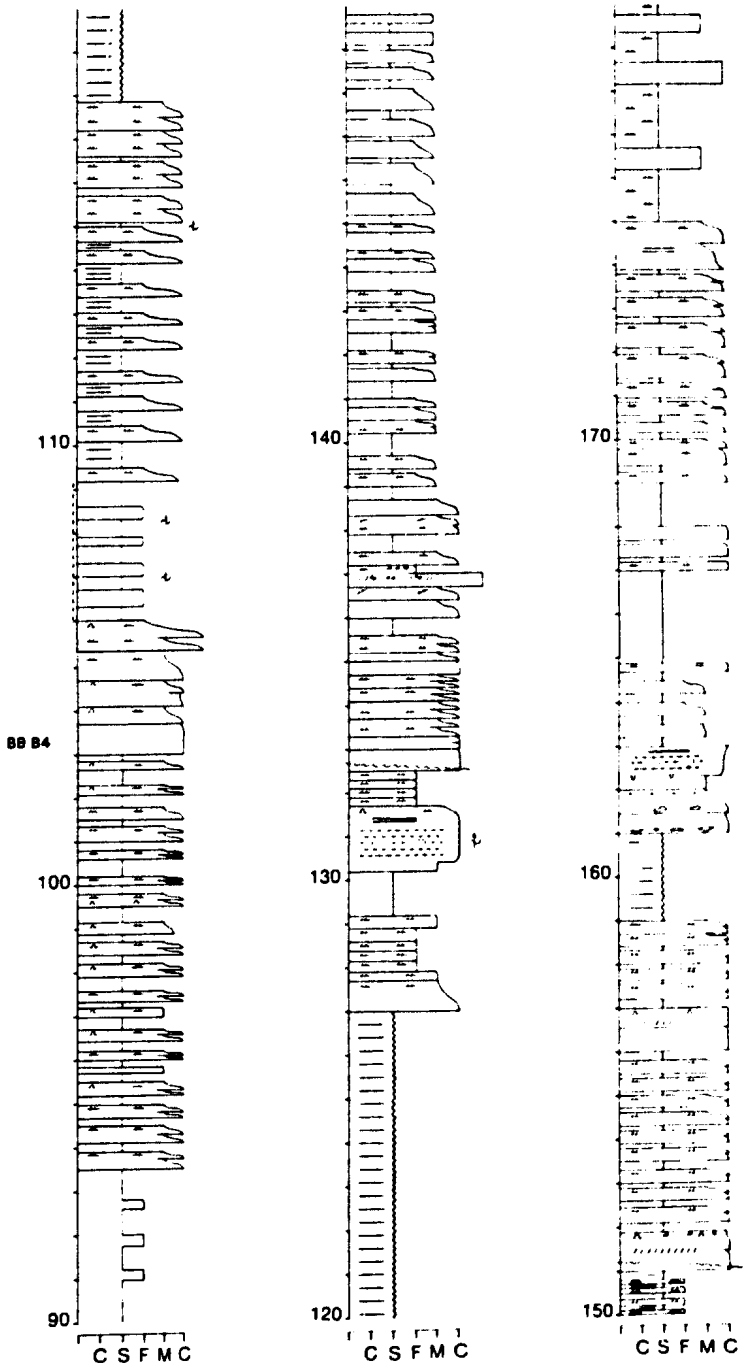
Other comments: Another example of sand-rich American Tickle formation.

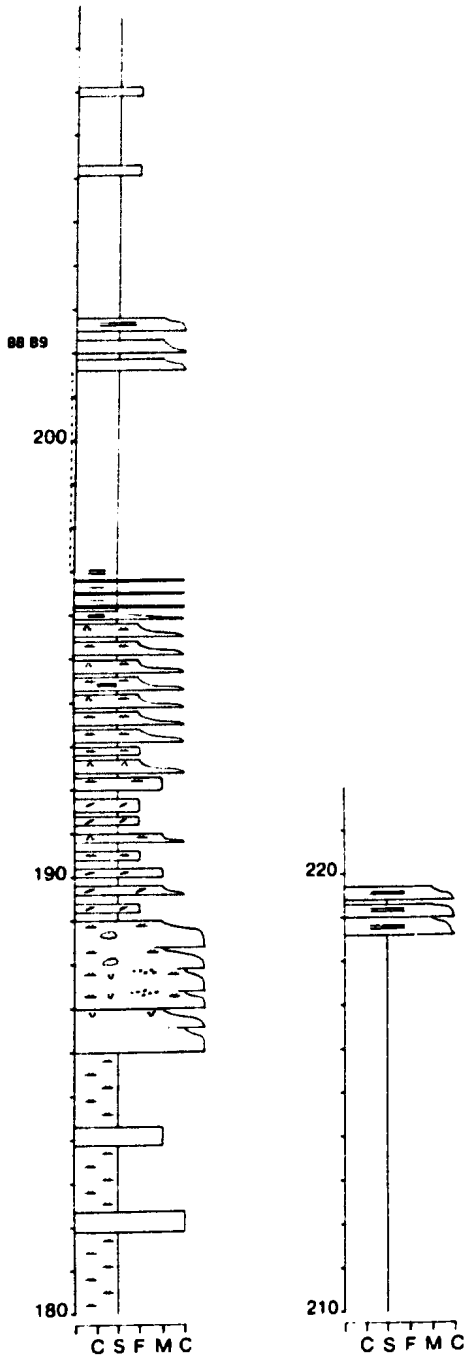
Paleocurrent data:

Bellburns

N=8


0
10
20
C S F M C
30
40
50
BB B2
C S F M C
60
70
80
C S F M C


110
100
90
B8 B4
140
130
120
170
160
150
C S F M C
C S F M C
C S F M C


88 89
200
190
180
C S F M C
220
210
C S F M C

A2.1.6 Other Localities

Note: other localities are noted because they display some important feature not shown by the selected sections above.

1. Howe Harbour.

Grid Reference: NTS 2M/5 and 2M/6 WG 740895.

Exposure: Low lying coastal exposure. Intertidal zone.

Comments: The type locality for the Howe Harbour Member. Several HH2 conglomerate beds approximately 1 m thick are exposed here as well as HH1 shale chip layers interbedded with silty argillites of the American Tickle formation. The uppermost contact of the American Tickle formation with the Northwest Arm Formation is in close proximity but is poorly exposed. Complex structure.

SECTION A2.2 MAINLAND FORMATION

A2.2.1, A2.2.2, A2.2.3 Three Rock Cove

Grid Reference: NTS 12B/11 UD 12B/11 UD 420851 to 408837

Exposure: Cliff-like exposure with wide pebbly beach.

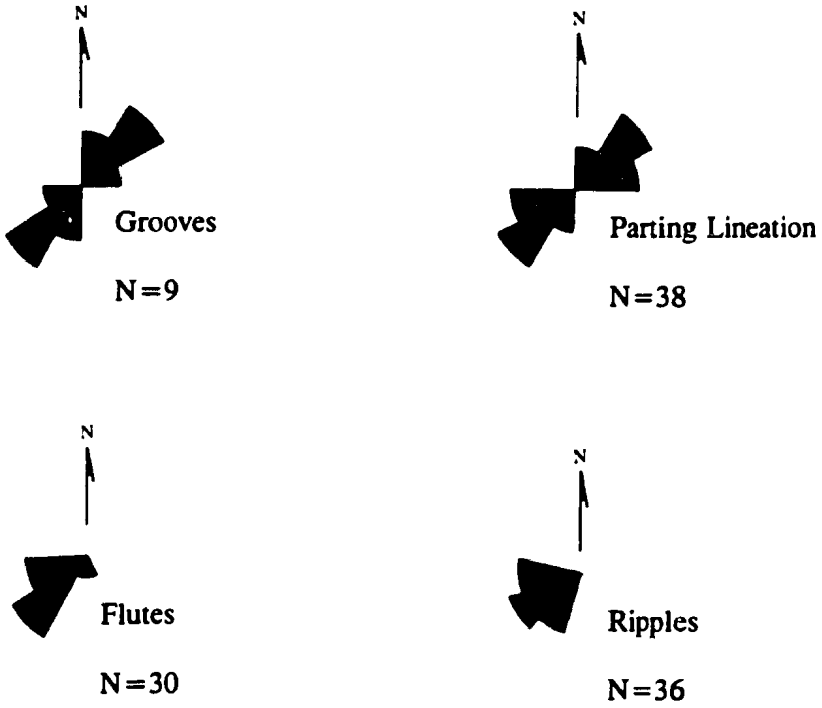
Structure: Within the main Three Rock Cove section, no obvious major structural discontinuities were observed. Faults occur between the top of the main Three Rock Cove section and Three Rock Cove A, and between Three Rock Cove A and B. Between the faults Three Rock Cove A and B appear to be intact. It is not known whether Three Rock Cove A and B represent sections which are younger, older, or equivalent in age to the main section.

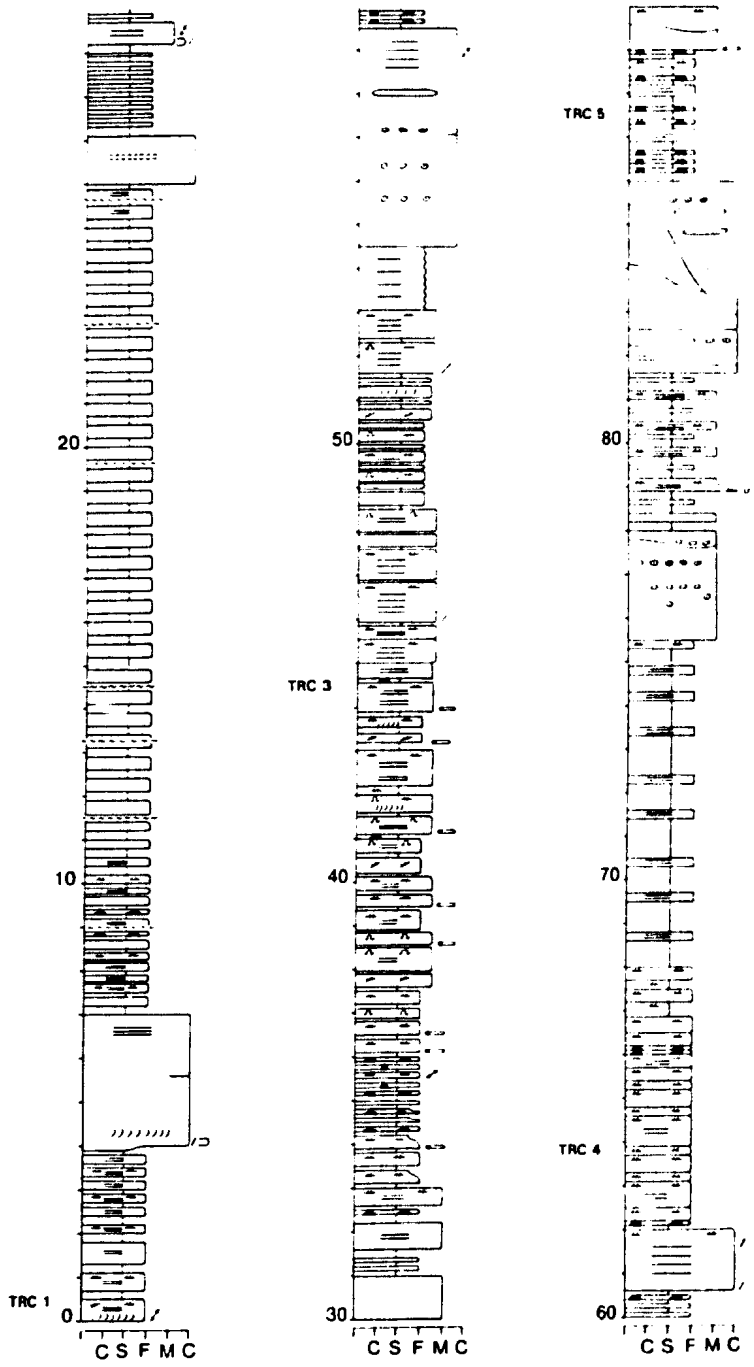
Underlying unit: The base of the unit is not exposed. The base of the main section was taken as the lowermost exposed thick bed at Crow Head.

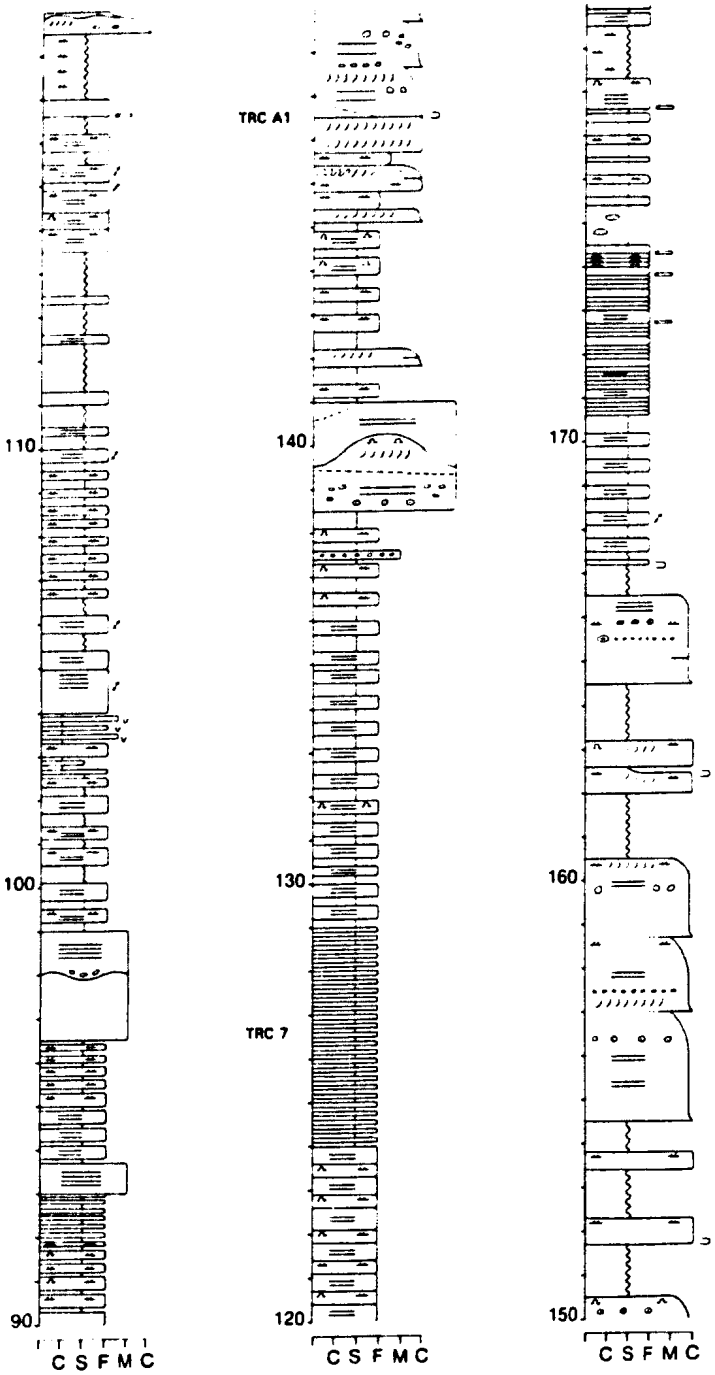
Overlying unit: The top of the unit is not exposed.

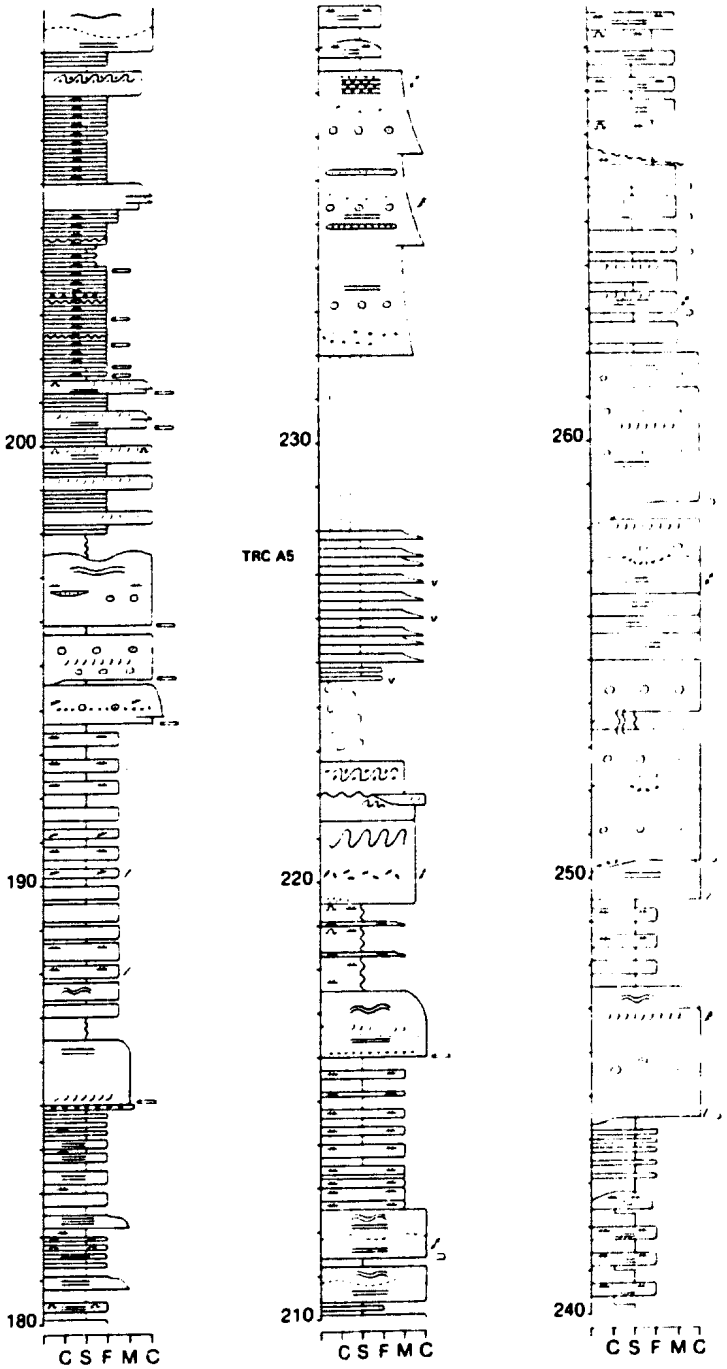
Other comments: This is the type section for the Mainland formation.

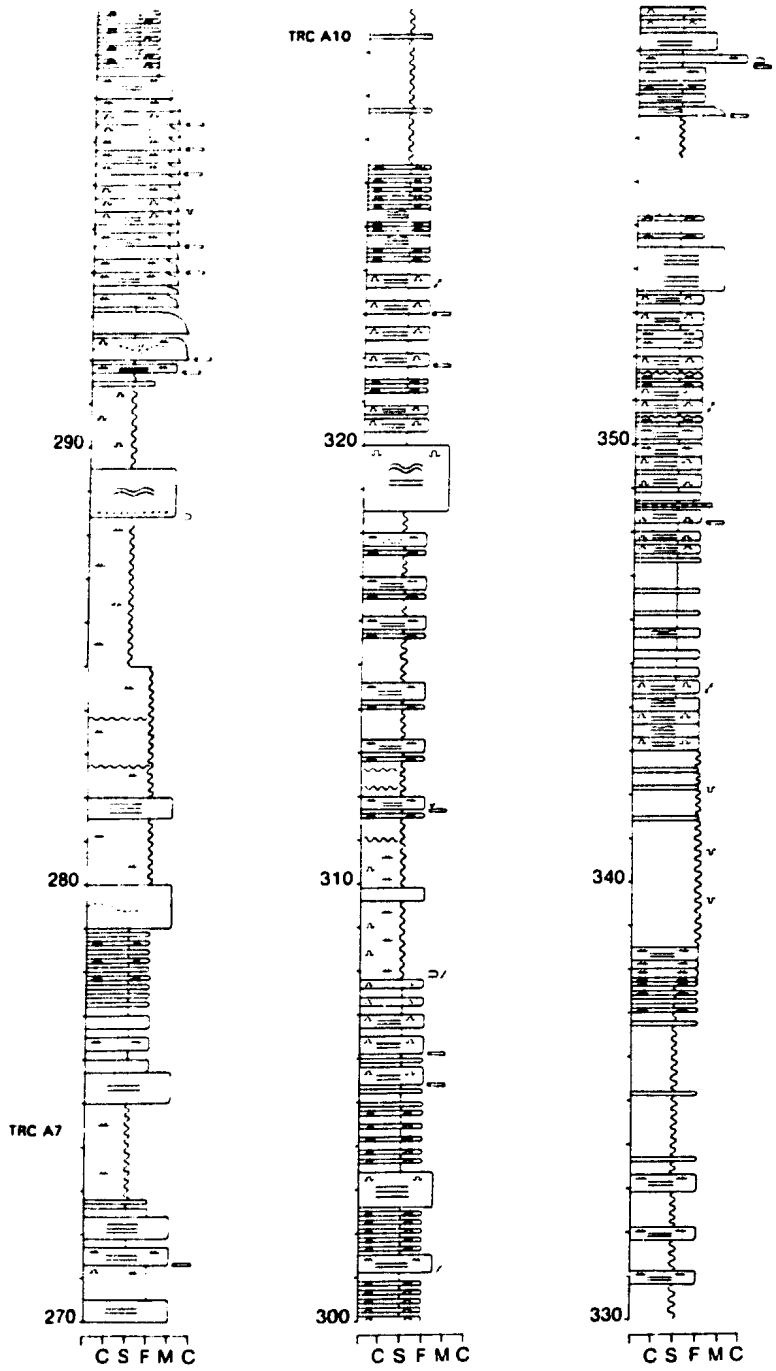
Paleocurrent data:

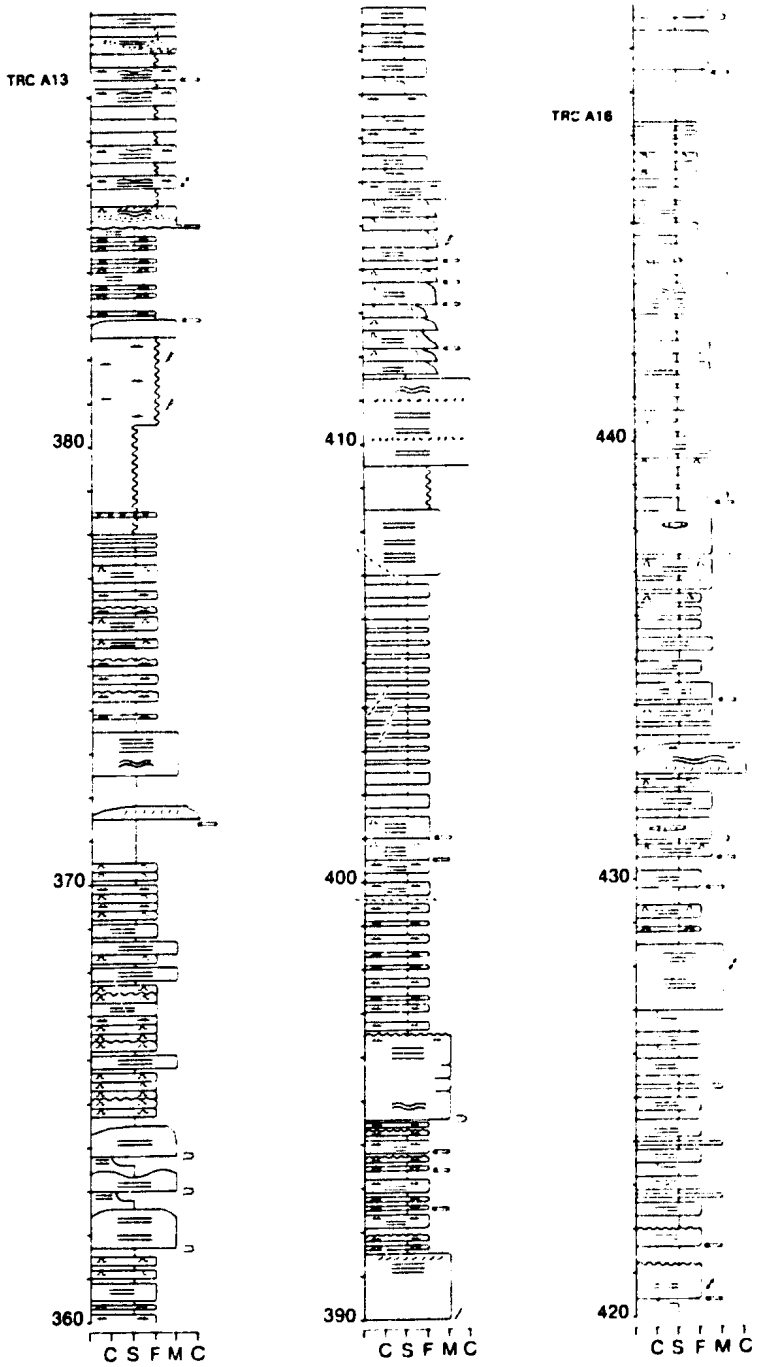


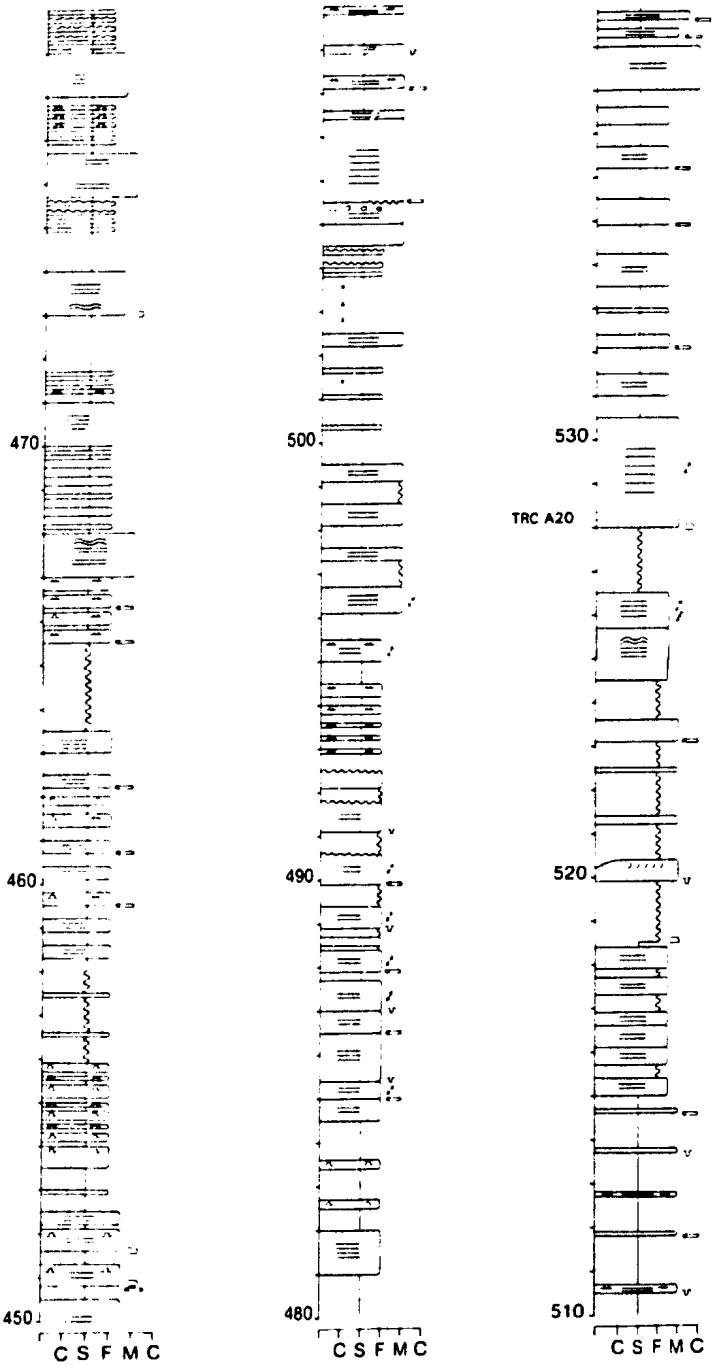

TRC 1
0
10
20
TRC 3
30
40
50
TRC 4
60
70
80
TRC 5
C S F M C
C S F M C
C S F M C


TRC A1
TRC 7
110
100
90
140
130
120
170
160
150
C S F M C
C S F M C
C S F M C


200
190
180
230
TRC A5
220
210
260
250
240
C S F M C
C S F M C
C S F M C


TRC A7
TRC A10
270
280
290
300
310
320
330
340
350
C S F M C
C S F M C
C S F M C


TRC A13
380
370
360
C S F M C
410
400
390
C S F M C
TRC A16
440
430
420
C S F M C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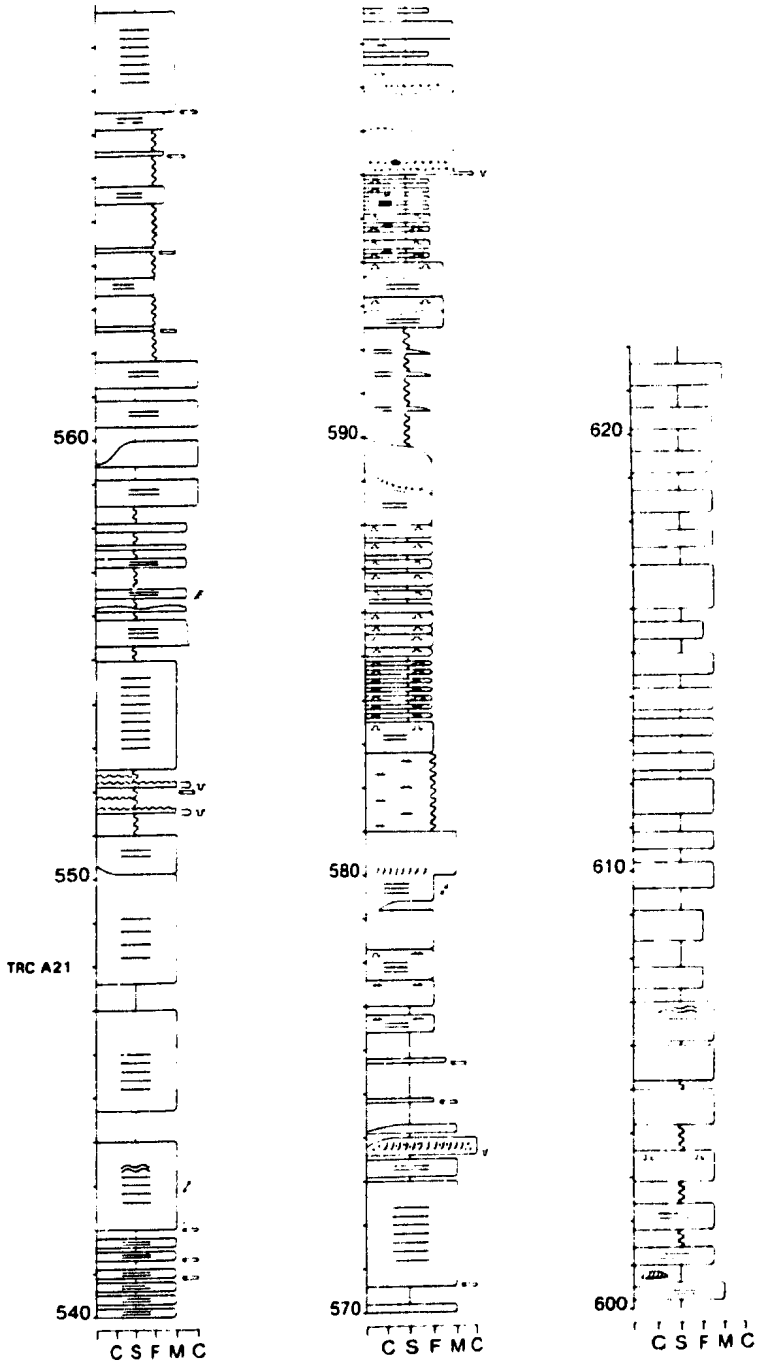
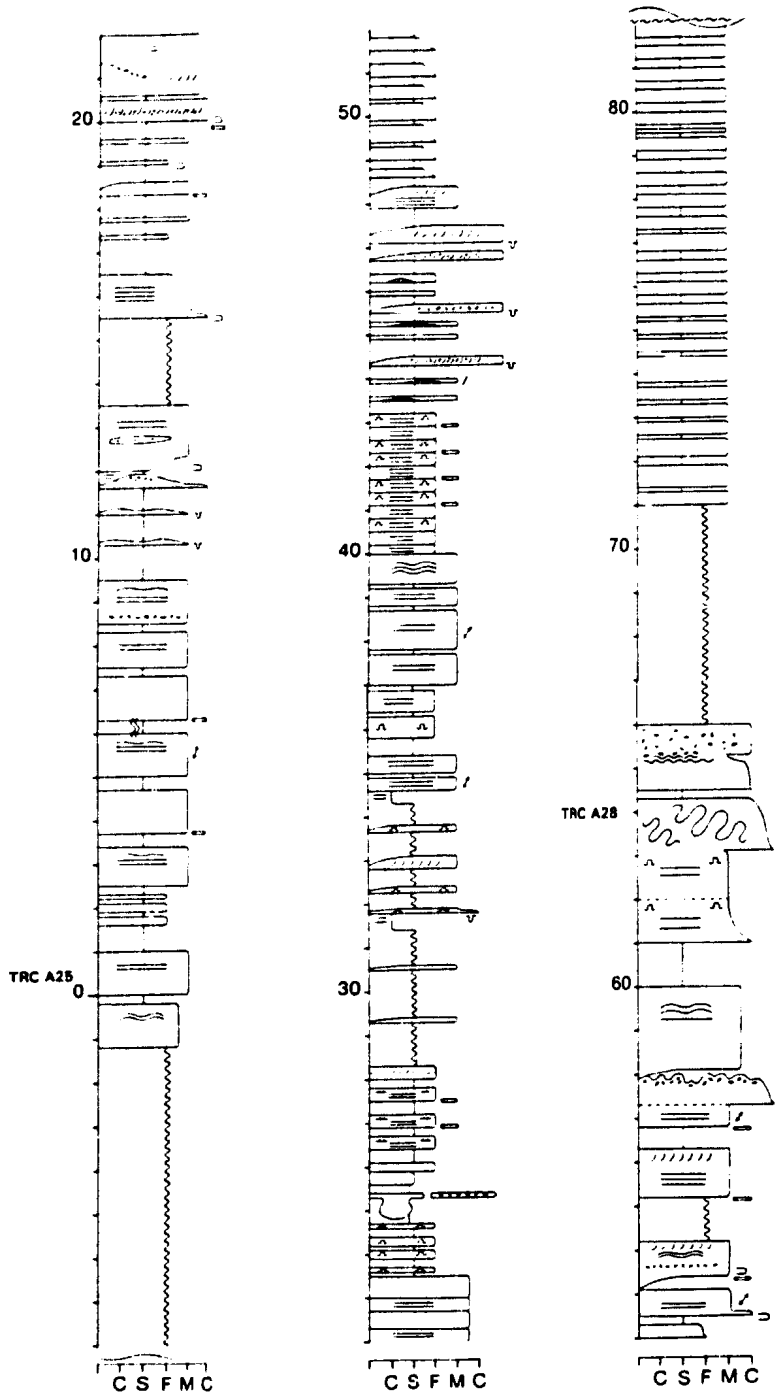
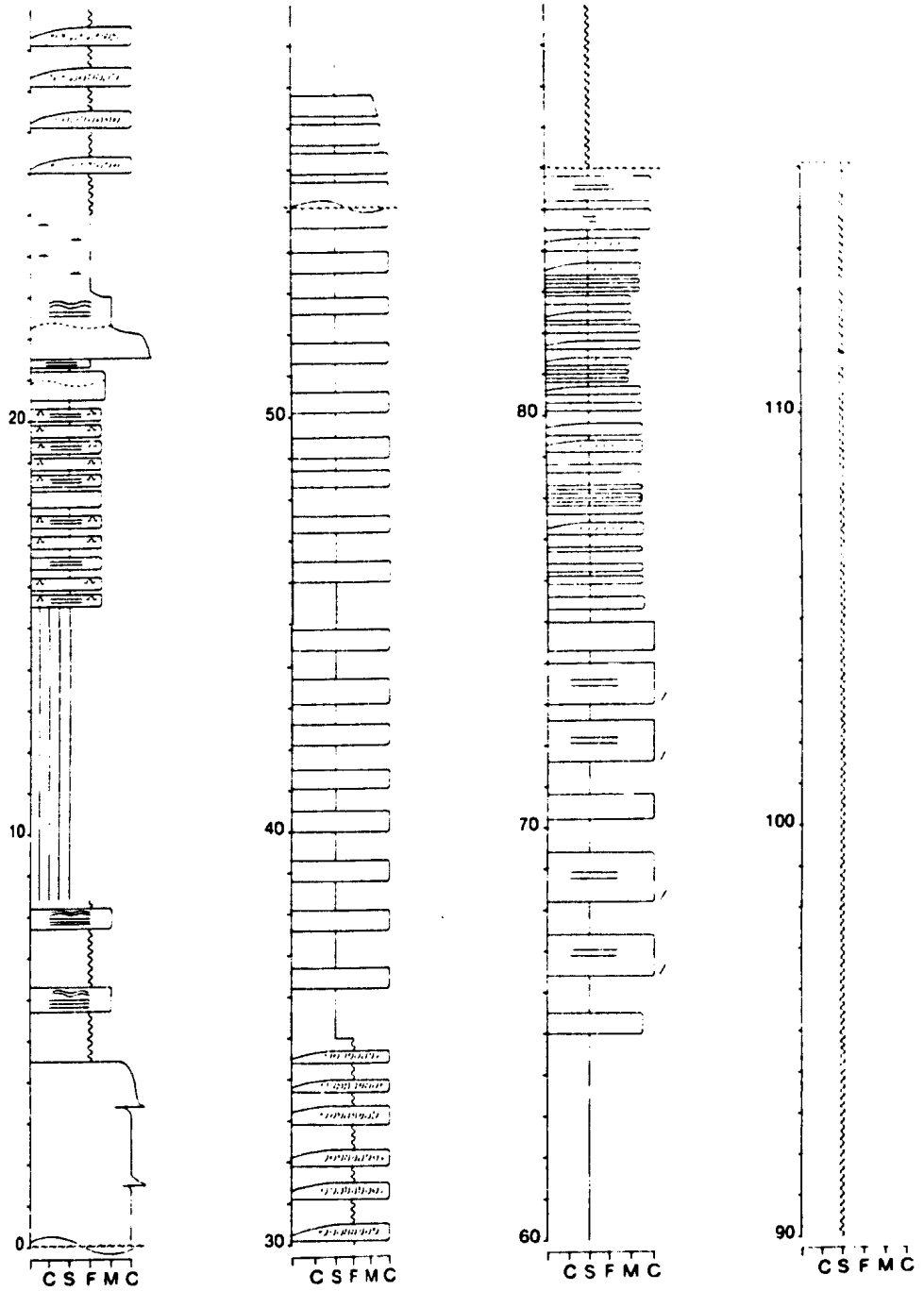
460
450
C S F M C
500
490
480
C S F M C
530
TRC A20
520
510
C S F M C


560
550
TRC A21
540
590
580
570
620
610
600
C S F M C
C S F M C
C S F M C


TRC A25
0
10
20
30
40
50
60
70
TRC A28
80
C S F M C
C S F M C
C S F M C


0
10
20
30
40
50
60
70
80
90
100
110
C S F M C
C S F M C
C S F M C
C S F M C

A2.2.4 Other Localities

Note: other localities are noted because they display some important feature not shown by the selected sections above.

1. Mainland

Grid Reference: NTS 12B/11 UD382803.

Exposure: cliff-like exposure with a wide pebbly beach.

This is a 15 m section which overlies the type section of the Cape Cormorant Formation. It consists of thin-medium bedded turbidites, and shows anomalous paleocurrent directions to the northwest.

2. Low Point

Grid Reference: NTS 12B/11 UD399831.

Exposure: Low lying coastal exposure.

This is a 64 m section which may represent the topmost Mainland formation. The section overlies sheared grey-green shales, and contains mainly thick to very thick-bedded sandstones, showing cross-bedding in sets up to 1 m thick. Graptolites indicative of a Llandeilo age have been reported from this locality (James and Stevens, 1982).

SECTION A2.3 LOWER HEAD FORMATION

A2.3.1 Martin Point North

Grid Reference: NTS 12H/13 VF 349133.

Exposure: Low lying coastal exposure. Intertidal zone.

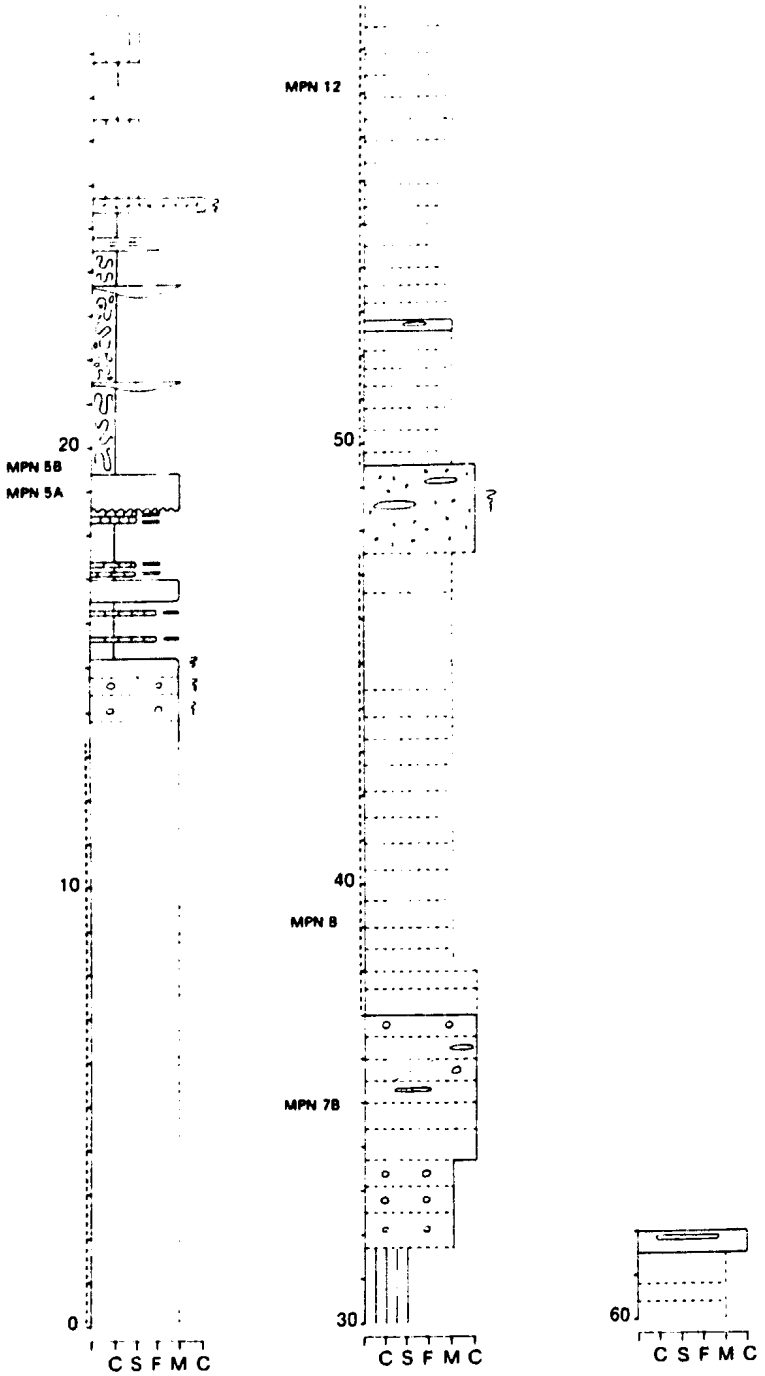
Structure: Appears simple.

Underlying unit: Green Point Formation of the Cow Head Group. Contact not well exposed, but appears sharp. Base of the section is at the inferred contact between the Cow Head Group and the Lower Head Formation.

Overlying unit: The top of the unit is not exposed.

Other comments: Displays chaotic shales at its base.

Paleocurrent data: Insufficient data available.


MPN 12
MPN 5B
MPN 5A
MPN 8
MPN 7B
0
10
20
30
40
50
60
C S F M C
C S F M C
C S F M C

A2.3.2 Martin Point South

Grid Reference: NTS 12H/13 VF 341124.

Exposure: Low lying coastal exposure. Intertidal zone.

Structure: Appears simple. Some features may indicate syndepositional tectonics.

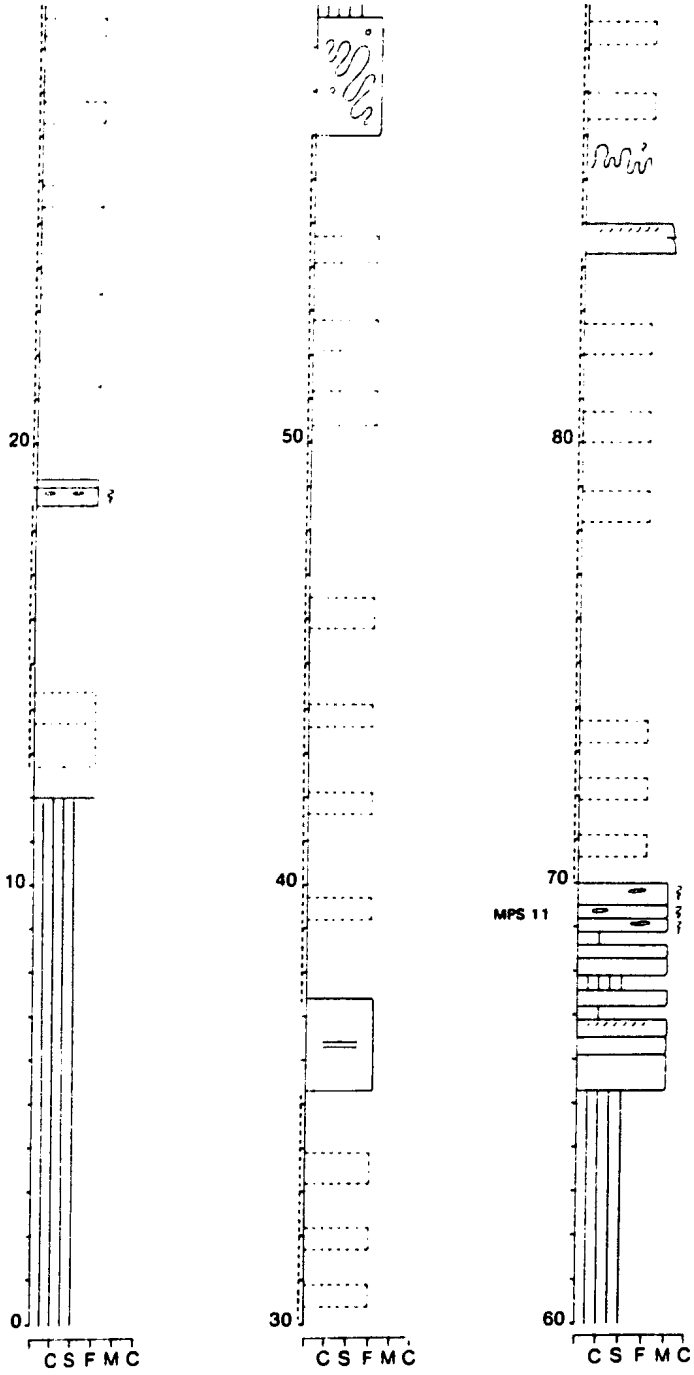
Underlying unit: Green Point Formation of the Cow Head Group. Contact not well exposed, but appears sharp. The base of the section is at the inferred contact between the Cow Head Group and the Lower Head Formation.

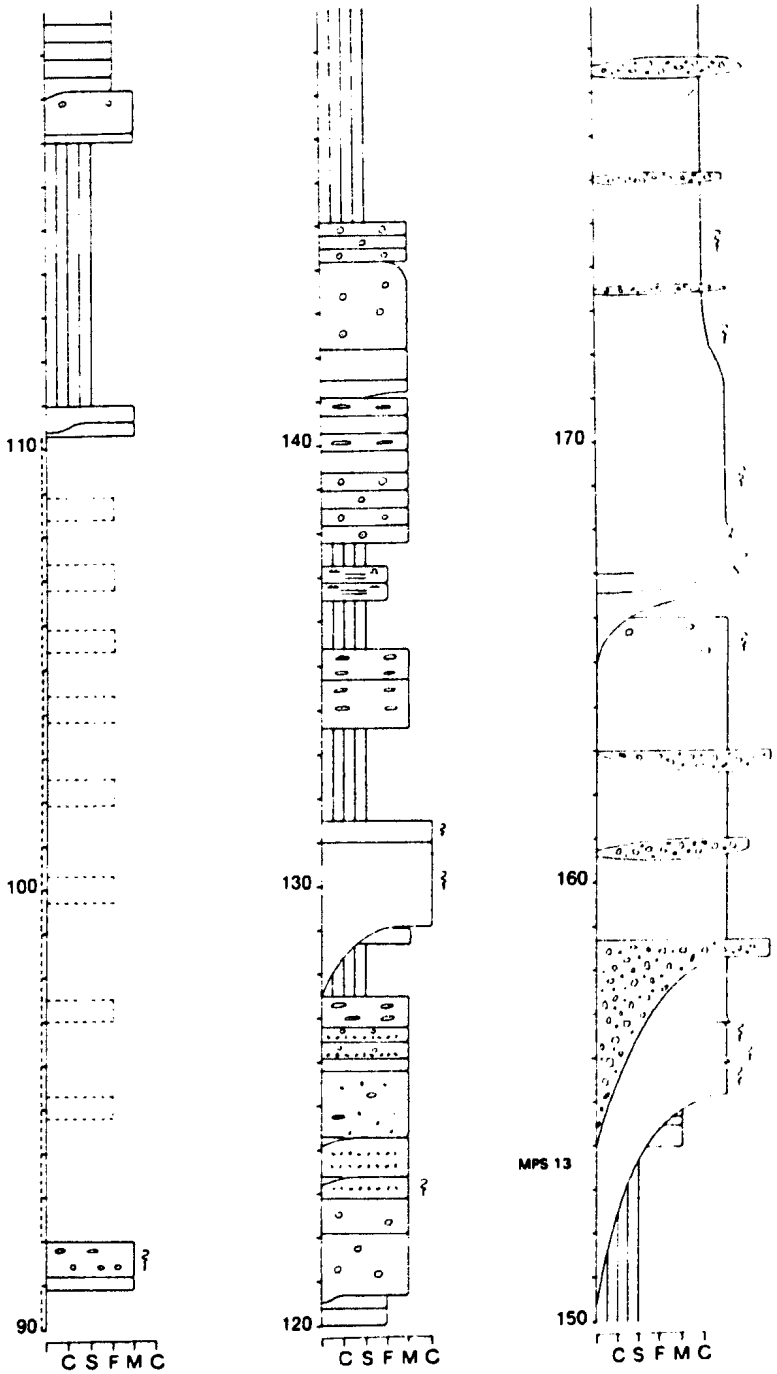
Overlying unit: The top of the unit is not exposed.

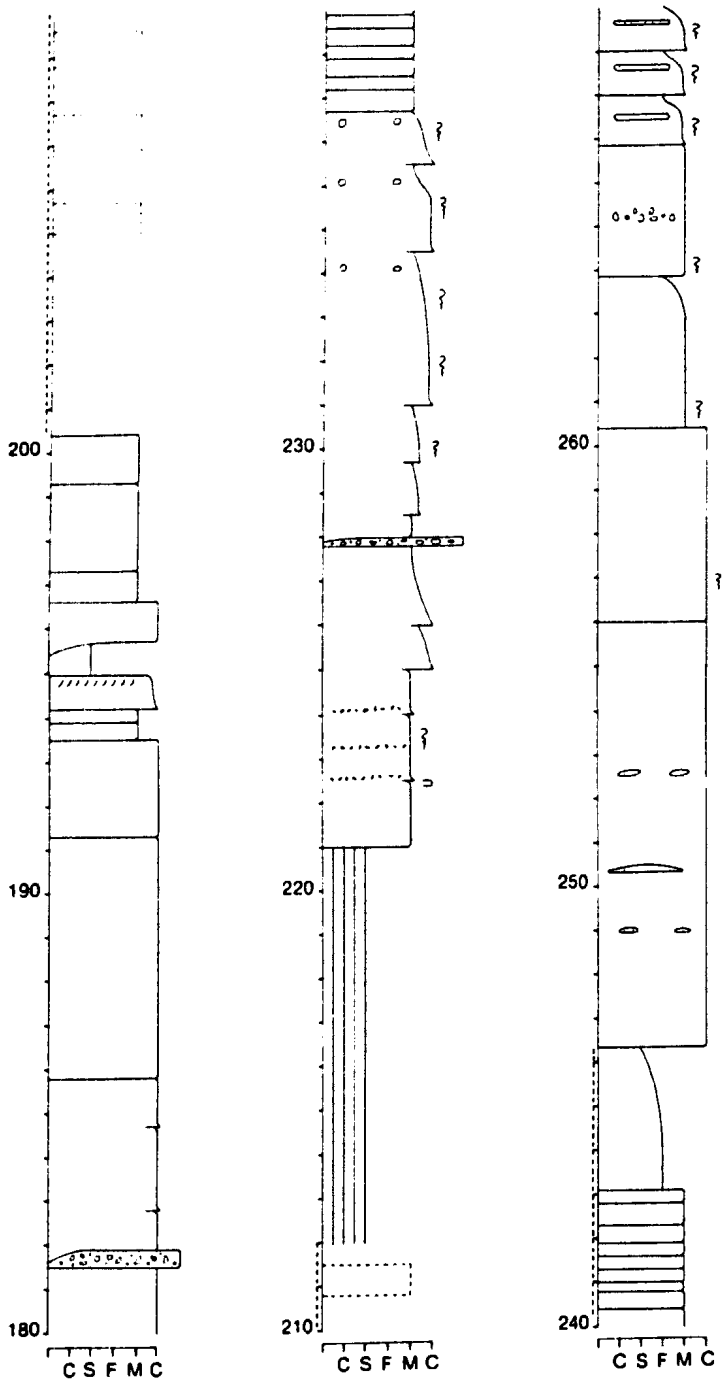
Other comments: This section displays good examples of facies LH1 conglomerates and very coarse sandstones.

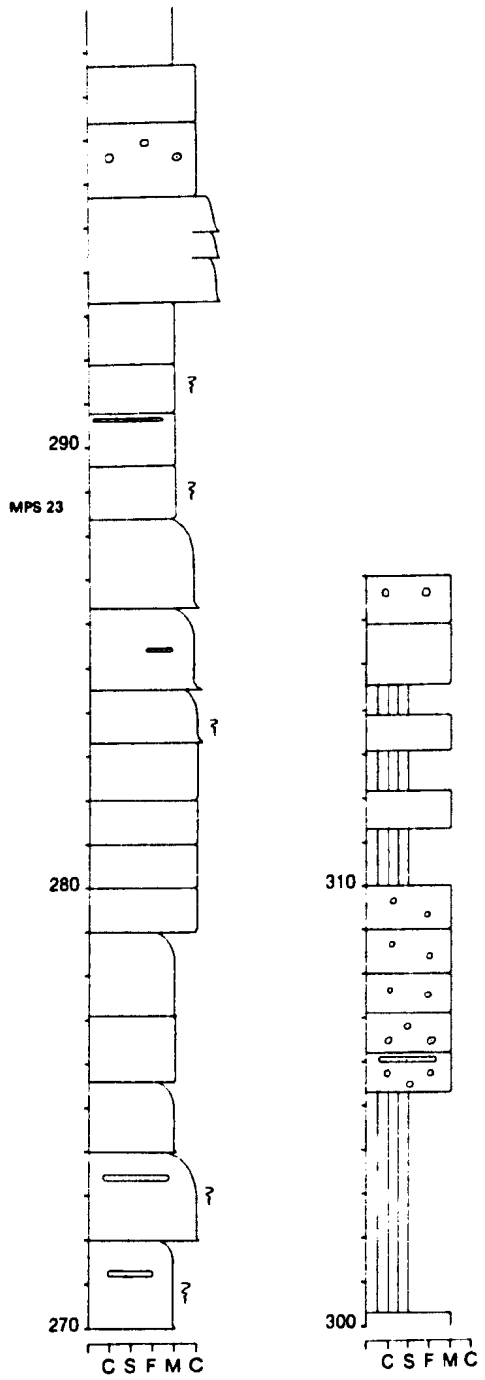
Paleocurrent data: Insufficient data available.

Martin Point South




110
100
90
C S F M C
140
130
120
C S F M C
170
160
MPS 13
150
C S F M C


200
190
180
230
220
210
260
250
240
C S F M C
C S F M C
C S F M C


290
MPS 23
280
270
C S F M C
310
300
C S F M C

A2.3.3 Western Brook Pond North

Grid Reference: NTS 12H/13 VF 402153 to 413152

Exposure: Low cliff-like exposure at edge of pond.

Structure: Section is exposed in the western limb of an upright syncline. Appears simple within the section shown, but the base of the unit is a complex folded/faulted zone consisting of a basal zone of sandstones a few m thick overlain by folded and faulted shales and cherts of lithologies similar to the Cow Head Group.

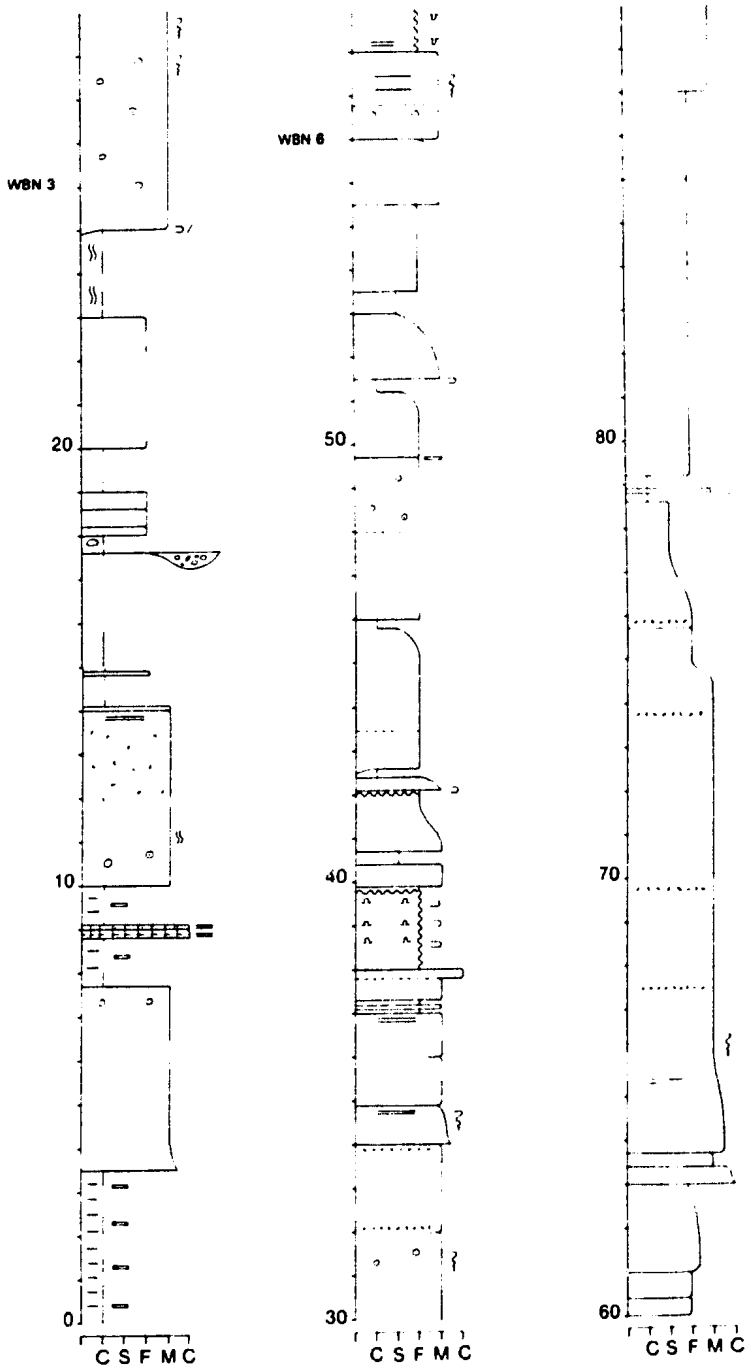
Underlying unit: Green Point Formation of the Cow Head Group. The base of the section shown is taken at the first undeformed bed above the deformed zone of red and green shales. Since the base of the Lower Head Formation is defined as the first sandstone bed, the deformed zone of red and green shales is included in the Lower Head Formation. Hence a considerable thickness of Lower Head Formation may have been excluded from the section.

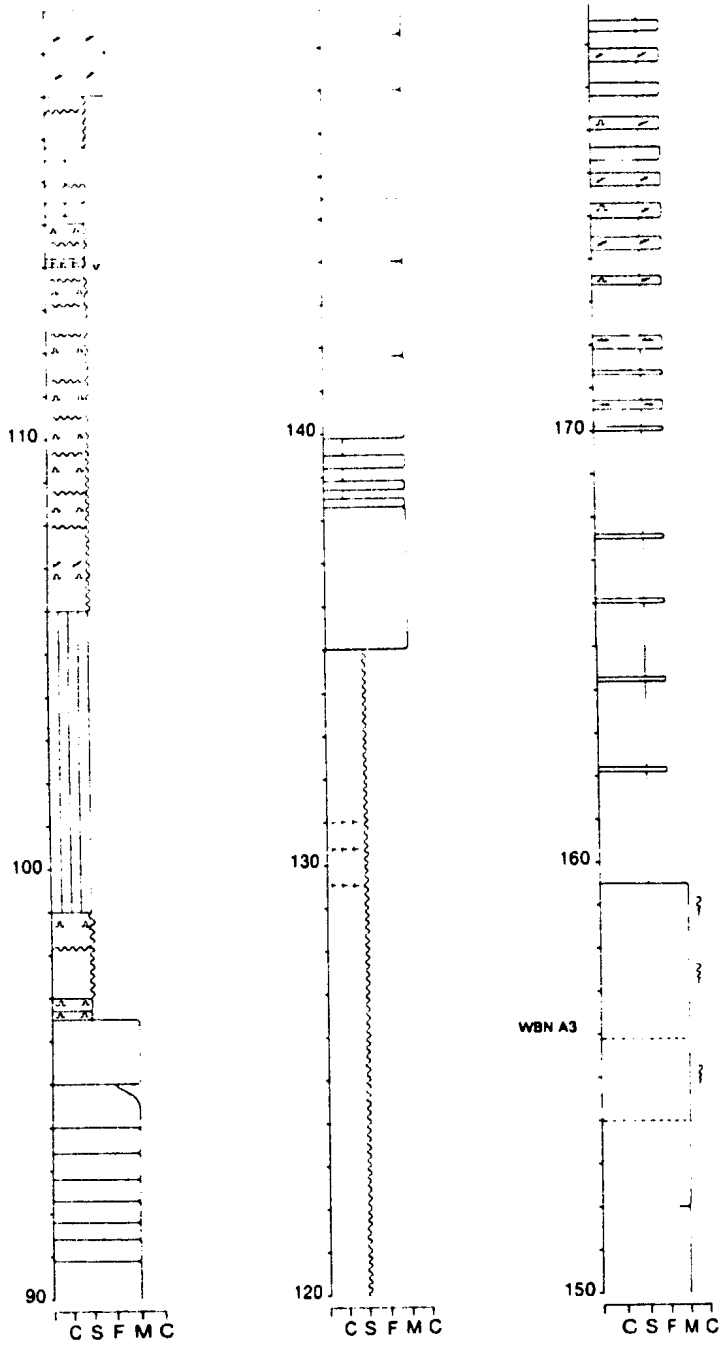
Overlying unit: Top of the unit is not exposed.

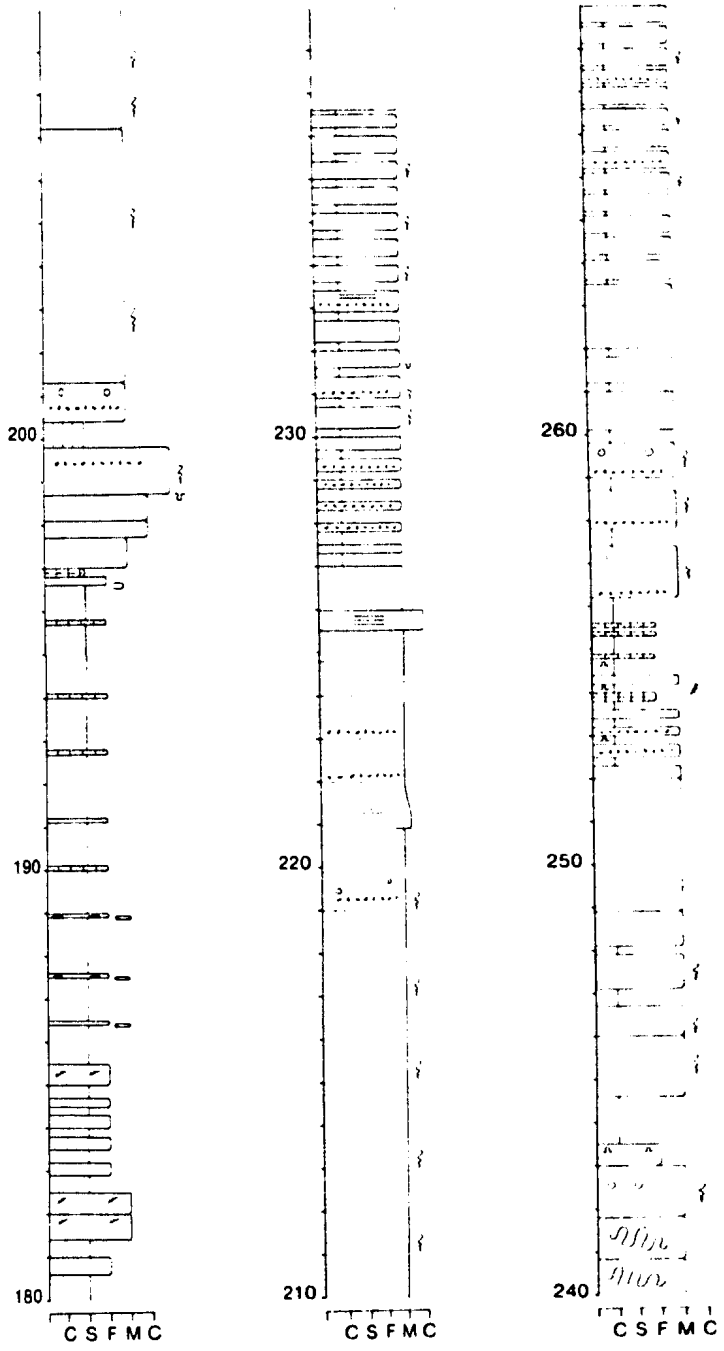
Other comments: This section is of interest because it contains a wider variety of facies than many of the coastal sections. Given that this represents only a partial section through the unit, the Western Brook Pond North Section probably represents one of the thickest sections through the Lower Head Formation.

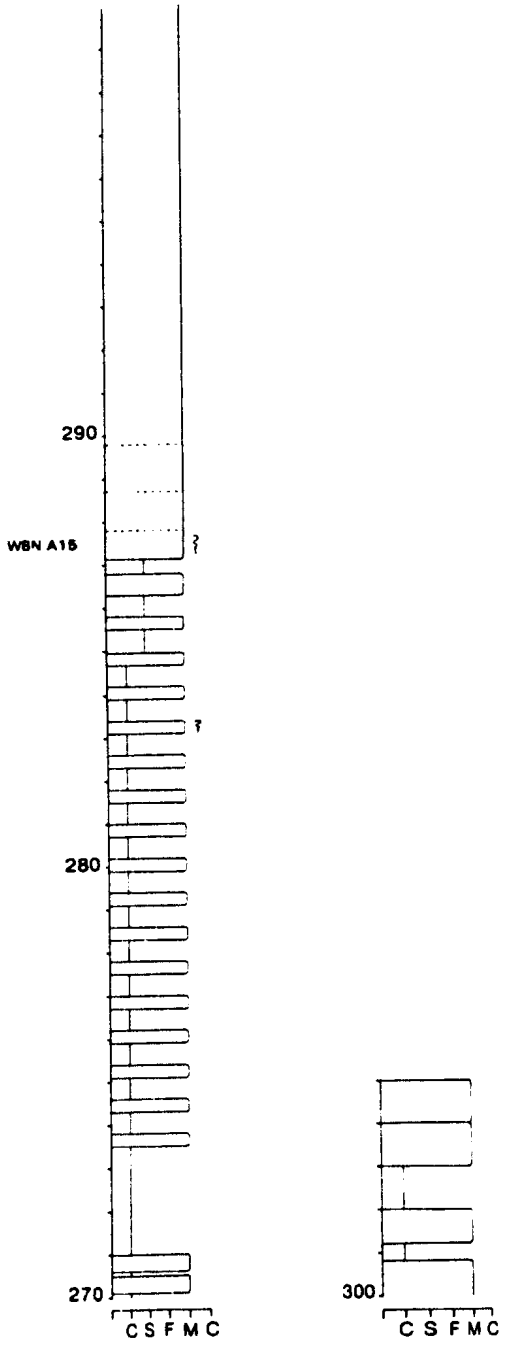
Paleocurrent data: Insufficient data available.

Western Brook Pond North




110
100
90
C S F M C
140
130
120
C S F M C
170
160
WBN A3
150
C S F M C


200
190
180
C S F M C
230
220
210
C S F M C
260
250
240
C S F M C


290
WBN A15
280
270
C S F M C
300
C S F M C

A2.3.4 Other Localities

Note: other localities are noted because they display some important feature not shown by the selected sections above.

1. Black Point

Grid Reference: NTS 12B/10 UD 756846.

This cliff-like coastal section is approximately 120 m thick and contains excellent examples of LH1 facies (conglomerates and very coarse sandstones), with multiple spectacular amalgamation surfaces.

2. Portland Hill

Grid Reference: NTS 12H/13 VF 552548.

This prominent hill, although exposure is poor, appears to contain a very thick section (?450 m) of facies LH1, and may possibly represent a narrow, deep channel fill. The lithology is pebble to cobble conglomerate, with clasts dominated by fine grained limestone and calcarenite.

3. Portland Creek

Grid Reference: NTS 21I/4 VF 559568.

This is a low lying coastal exposure, which is only exposed at low tide. It is structurally more complex than many Lower Head sections, and the top and base of the unit are not exposed. However a minimum of 300 m of section is exposed. Facies present include thick packages of LH6 mudstone interbedded with LH2 medium to very thick-bedded sandstone. An olistostrome is exposed near the top of the exposed section. The LH2 facies near the top of the exposed section contain granule layers similar tc clasts in the Portland Hill conglomerate.

APPENDIX 3 ELECTRON MICROPROBE DATA

The majority of electron microprobe analyses were carried out at the University of Manitoba on a CAMECA SX 50 microprobe, under operating 15 kv and 20 namp with a 5 micron beam. Other analyses were carried out at the University of Saskatchewan on a JEOL superprobe under similar operating conditions.

The designators 1dot, 2dot, #, ksp1, pl5 etc. are internal designators for location of spots on specific grains.

Note that for feldspars and chromite, totals under 97% and over 102% were excluded from further consideration. For chlorites all totals were considered. Poor polish was responsible for low totals. This is a common problem in chlorites, and it has been suggested (Laird, 1988) that the proportions of elements present are not substantially altered.

Recalculation of ions for chlorite was carried out using the procedure in Deer, Howie and Zussmann (1966). Chlorites were recalculated on the basis of 28 oxygens.

CHLORITE DATA GOOSE TICKLE

	PCP-B1 2DOT	PCP-B1 3DOT	PCP-B1 5DOT	PCP-B1 7DOT	PCP-B1 8DOT	PCP-B1 4DOT	PCP-B1 #10	PCP-B1 #11	PCP-B1 #12	PCP-B1 1DOT	PCP-B1 1 DOT
Na_2O	3.551	0.000	0.012	0.004	0.000	0.000	0.048	0.020	0.005	0.004	0.000
FeO	10.452	19.377	21.485	22.014	20.803	26.058	21.153	25.034	17.944	28.435	21.011
K_2O	0.064	0.018	0.022	0.035	0.022	0.628	0.062	0.015	0.014	0.004	0.023
MgO	4.240	18.685	16.066	16.315	18.917	13.051	17.568	15.723	21.708	10.784	17.126
TiO_2	0.117	0.000	0.000	0.000	0.029	0.000	0.000	0.000	0.000	0.043	0.000
SiO_2	43.047	29.413	28.210	30.157	29.409	31.517	28.822	28.459	29.092	25.558	28.375
Al_2O_3	25.136	17.426	19.125	17.608	18.046	13.689	18.365	15.580	16.643	22.377	18.926
MnO	0.100	0.487	0.058	0.067	0.065	0.184	0.029	0.174	0.203	0.263	0.076
CaO	0.465	0.249	0.219	0.221	0.224	0.118	0.365	0.113	0.087	0.092	0.337
NiO	0.085	0.086	0.283	0.208	0.278	0.117	0.229	0.022	0.060	0.023	0.291
P_2O_5	0.176	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.049	0.025
Cr_2O_3	0.000	0.048	0.293	0.464	0.144	0.046	0.282	0.025	0.315	0.039	0.148
TOTAL	87.433	85.789	85.773	87.093	87.937	85.408	86.924	85.165	86.071	87.671	86.338

CHLORITE DATA GOOSE TICKLE (continued)

	TC4 1DOT	TC4 2 DOT	TC4 3DOT	TC4 5DOT	TC4 6DOT
Na_2O	0.014	0.000	0.047	0.030	0.021
FeO	20.965	21.971	22.249	22.234	22.169
K_2O	0.037	0.023	0.077	0.063	0.062
MgO	18.615	15.931	16.118	16.171	16.704
TiO_2	0.000	0.000	0.055	0.000	0.000
SiO_2	30.011	29.362	29.291	28.543	29.104
Al_2O_3	17.484	19.047	18.794	19.937	18.315
MnO	0.064	0.053	0.101	0.037	0.049
CaO	0.246	0.270	0.271	0.247	0.195
NiO	0.043	0.100	0.081	0.072	0.096
P_2O_5	0.009	0.002	0.000	0.000	0.000
Cr_2O_3	0.584	0.253	0.097	0.129	0.074
TOTAL	88.072	87.012	87.181	87.463	86.798

Goose Tickle Chlorite Ions

	PCP-B1 (1 dot)	PCP-B1 (1 dot)	PCP-B1 (2 dot)	PCP B1 (3 dot)
Na	0.00	0.00	1.28	0.00
Fe	5.08	3.67	1.63	3.37
K	0.00	0.01	0.02	0.00
Mg	3.43	5.33	1.18	5.80
Ti	0.01	0.00	0.02	0.00
Si	5.46	5.92	8.02	6.12
Al	5.63	4.65	5.52	4.28
Mn	0.05	0.01	0.02	0.09
Ca	0.02	0.08	0.09	0.06
Ni	0.00	0.05	0.01	0.01
P	0.01	0.00	0.03	0.00
Cr	0.01	0.02	0.00	0.01
Fe/Mg	1.48	0.69	1.38	0.58
Fe/Fe+Mg	0.60	0.41	0.58	0.37
Mg/Fe+Mg	0.40	0.59	0.42	0.63
Al/(Al+Fe+Mg)	0.40	0.34	0.66	0.32

	PCP B1 (5 DOT)	PCP B1 (7 DOT)	PCP B1 (8 DOT)	PCP B1 (4 DOT)
Na	0.00	0.00	0.00	0.00
Fe	3.78	3.81	3.55	4.72
K	0.01	0.01	0.01	0.17
Mg	5.04	5.04	5.76	4.21
Ti	0.00	0.00	0.00	0.00
Si	5.94	6.25	6.01	6.82
Al	4.74	4.30	4.34	3.49
Mn	0.01	0.01	0.01	0.03
Ca	0.05	0.05	0.05	0.03
Ni	0.05	0.03	0.05	0.02
P	0.00	0.00	0.00	0.00
Cr	0.05	0.08	0.02	0.01
Fe/Mg	0.75	0.76	0.62	1.12
Fe/Fe+Mg	0.43	0.43	0.38	0.53
Mg/Fe+Mg	0.57	0.57	0.62	0.47
Al/(Al+Fe+Mg)	0.35	0.33	0.32	0.28

	PCP-B1 #10	PCP-B1 #11	PCP-B1 #12	TC4 1DOT
Na	0.02	0.01	0.00	0.01
Fe	3.67	4.54	3.10	3.58
K	0.02	0.00	0.00	0.01
Mg	5.43	5.08	6.68	5.66
Ti	0.00	0.00	0.00	0.00
Si	5.98	6.17	6.00	6.12
Al	4.49	3.98	4.05	4.20
Mn	0.01	0.03	0.04	0.01
Ca	0.08	0.03	0.02	0.05
Ni	0.04	0.00	0.01	0.01
P	0.00	0.00	0.00	0.00
Cr	0.05	0.00	0.05	0.09
Fe/Mg	0.68	0.89	0.46	0.63
Fe/Fe+Mg	0.40	0.47	0.32	0.39
Mg/Fe+Mg	0.60	0.53	0.68	0.61
Al/(Al+Fe+Mg)	0.33	0.29	0.29	0.31

	TC4 2DOT	TC4 3DOT	TC4 5DOT	TC4 6DOT
Na	0.00	0.02	0.01	0.01
Fe	3.80	3.85	3.84	3.86
K	0.01	0.02	0.02	0.02
Mg	4.92	4.98	4.98	5.18
Ti	0.00	0.01	0.00	0.00
Si	6.08	6.07	5.89	6.06
Al	4.65	4.59	4.85	4.49
Mn	0.01	0.02	0.01	0.01
Ca	0.06	0.06	0.05	0.04
Ni	0.02	0.01	0.01	0.02
P	0.00	0.00	0.00	0.00
Cr	0.04	0.02	0.02	0.01
Fe/Mg	0.77	0.77	0.77	0.74
Fe/Fe+Mg	0.44	0.44	0.44	0.43
Mg/Fe+Mg	0.56	0.56	0.56	0.57
Al/(Al+Fe+Mg)	0.35	0.34	0.35	0.33

CHLORITE DATA LOWER HEAD

	El6 #12	El6 #13	El6 #15	El6 2DOT	BP10 8 DOT	BP10 SQUARE	BP10 7 DOT	BP10 3DOT	BP10 4DOT
Na_2O	0.010	0.008	0.000	0.008	0.025	0.022	0.027	0.000	0.000
FeO	17.771	18.533	30.950	20.740	21.170	18.448	29.013	31.538	26.461
K_2O	0.409	0.050	0.004	0.020	0.042	0.065	0.035	0.020	0.003
MgO	18.722	20.199	11.640	19.743	19.395	20.454	13.187	11.616	14.427
TiO_2	0.118	0.012	0.033	0.039	0.038	0.000	0.037	0.028	0.024
SiO_2	27.079	27.099	24.340	31.108	30.655	31.131	27.315	25.345	26.212
Al_2O_3	20.531	19.183	18.405	13.784	16.015	18.037	16.701	17.739	18.960
MnO	0.185	0.156	0.293	0.189	0.388	0.226	0.309	0.154	0.337
CaO	0.057	0.094	0.009	0.093	0.132	0.319	0.178	0.030	0.074
NiO	0.090	0.128	0.014	0.122	0.015	0.080	0.031	0.028	0.032
P_2O_5	0.000	0.000	0.000	0.004	0.053	0.000	0.000	0.002	0.000
Cr_2O_3	0.160	0.067	0.029	0.042	0.038	0.197	0.018	0.025	0.058
	85.132	85.529	85.717	85.892	87.966	88.979	86.851	86.825	86.588

A 3.3

CHLORITE DATA LOWER HEAD - continued

	EI6 3DOT	EI6 4DOT	EI6 5DOT	EI6 #6	EI6 #7	EI6 #8	EI6 #9	EI6 #10	BP10 9DOTS
Na_2O	0.000	0.026	0.000	0.000	0.007	0.000	0.022	0.023	0.004
FeO	19.695	27.805	18.667	19.242	30.240	18.752	17.555	17.819	18.059
K_2O	0.022	0.967	0.034	0.021	0.003	0.027	0.004	0.033	0.024
MgO	19.690	8.595	20.422	19.371	12.957	20.761	21.79	22.081	19.996
TiO_2	0.031	0.000	0.000	0.000	0.017	0.000	0.022	0.000	0.055
SiO_2	29.114	29.674	30.543	29.267	29.441	30.377	32.568	31.805	30.935
Al_2O_3	18.367	18.525	17.731	17.710	14.785	18.447	16.844	15.509	18.060
MnO	0.156	0.225	0.148	0.097	0.254	0.098	0.117	0.162	0.291
CaO	0.073	0.036	0.116	0.060	0.036	0.096	0.113	0.104	0.260
NiO	0.049	0.073	0.120	0.141	0.000	0.140	0.090	0.093	0.089
P_2O_5	0.010	0.000	0.005	0.000	0.005	0.019	0.000	0.020	0.000
Cr_2O_3	0.088	0.014	0.080	0.078	0.000	0.075	0.039	0.020	0.011
TOTAL	87.295	85.940	87.866	85.987	87.745	88.792	89.164	87.669	87.784

CHLORITE DATA LOWER HEAD - continued

	BP10 5DOT	BP10 6DOT	BP10 2DOT	BP10 1DOT	El6 #16	El6 #17	El6 #18
Na_2O	0.015	0.016	0.038	0.025	0.000	0.012	0.000
FeO	17.207	19.323	12.548	28.459	17.454	18.749	16.399
K_2O	0.035	0.045	0.040	0.043	0.019	0.016	0.011
MgO	20.681	20.172	23.965	15.140	20.992	19.222	20.297
TiO_2	0.000	0.028	0.006	0.002	0.000	0.000	0.000
SiO_2	31.169	31.148	33.766	29.028	29.283	29.543	30.717
Al_2O_3	18.126	16.409	14.972	14.523	18.651	18.105	16.816
MnO	0.220	0.233	0.234	0.349	0.141	0.116	0.186
CaO	0.252	0.080	0.357	0.108	0.136	0.103	0.103
NiO	0.105	0.082	0.123	0.047	0.091	0.104	0.147
P_2O_5	0.000	0.000	0.015	0.002	0.000	0.010	0.000
Cr_2O_3	0.042	0.023	0.171	0.000	0.034	0.042	0.079
TOTAL	87.852	87.559	86.235	87.726	86.801	86.022	84.755

Chlorite Ions Lower Head

	EI6 #11	EI6 #12	EI6 #13	EI6 #15
Na	0.03	0.00	0.00	0.00
Fe	5.31	3.10	3.23	5.81
K	0.01	0.11	0.01	0.00
Mg	5.47	5.82	6.28	3.89
Ti	0.00	0.02	0.00	0.01
Si	4.19	5.65	5.65	5.46
Al	5.81	5.05	4.72	4.87
Mn	0.04	0.03	0.03	0.06
Ca	0.02	0.01	0.02	0.00
Ni	0.03	0.02	0.02	0.00
P	0.00	0.00	0.00	0.00
Cr	0.01	0.03	0.01	0.01
Fe/Mg	0.97	0.53	0.51	1.49
Fe/Fe+Mg	0.49	0.35	0.34	0.60
Mg/Fe+Mg	0.51	0.65	0.66	0.40
Al/(Al+Fe+Mg)	0.35	0.36	0.33	0.33

	EI6 #16	EI6 #17	EI6 #18	BP10 9DOTS
Na	0.00	0.00	0.00	0.00
Fe	2.97	3.23	2.83	3.03
K	0.00	0.00	0.00	0.01
Mg	6.36	5.91	6.25	5.99
Ti	0.00	0.00	0.00	0.01
Si	5.95	6.09	6.34	6.21
Al	4.47	4.40	4.09	4.27
Mn	0.02	0.02	0.03	0.05
Na	0.03	0.02	0.02	0.06
Ni	0.01	0.02	0.02	0.01
P	0.00	0.00	0.00	0.00
Cr	0.01	0.01	0.01	0.00
Fe/Mg	0.47	0.55	0.45	0.51
Fe/Fe+Mg	0.32	0.35	0.31	0.34
Mg/Fe+Mg	0.68	0.65	0.69	0.66
Al/(Al+Fe+Mg)	0.32	0.32	0.31	0.32

	BP10 8 DOT	BP10 SQUARE	BP10 7DOT	BP10 3DOT
Na	0.01	0.01	0.01	0.00
Fe	3.62	3.06	5.28	5.85
K	0.01	0.02	0.01	0.01
Mg	5.91	6.06	4.28	3.84
Ti	0.01	0.00	0.01	0.00
Si	6.27	6.18	5.94	5.62
Al	3.86	4.22	4.28	4.64
Mn	0.07	0.04	0.06	0.09
Ca	0.03	0.07	0.04	0.01
Ni	0.00	0.01	0.01	0.00
P	0.01	0.00	0.00	0.00
Cr	0.01	0.03	0.00	0.00
Fe/Mg	0.61	0.51	1.23	1.52
Fe/Fe+Mg	0.38	0.34	0.55	0.60
Mg/Fe+Mg	0.62	0.66	0.45	0.40
Al/(Al+Fe+Mg)	0.29	0.32	0.31	0.32

	BP10 4DOT	BP10 5DOT	BP10 6DOT	BP10 2DOT
Na	0.00	0.01	0.01	0.01
Fe	4.76	2.87	3.28	2.08
K	0.00	0.01	0.01	0.01
Mg	4.63	6.16	6.10	7.08
Ti	0.00	0.00	0.00	0.00
Si	5.64	6.22	6.32	6.70
Al	4.81	4.27	3.92	3.50
Mn	0.06	0.04	0.04	0.04
Ca	0.02	0.05	0.02	0.08
Ni	0.01	0.02	0.01	0.02
P	0.00	0.00	0.00	0.00
Cr	0.01	0.01	0.00	0.03
Fe/Mg	1.03	0.47	0.54	0.29
Fe/Fe+Mg	0.51	0.32	0.35	0.23
Mg/Fe+Mg	0.49	0.68	0.65	0.77
Al/(Al+Fe+Mg)	0.34	0.32	0.29	0.28

	BP10 1DOT	EI6 2DOT	EI6 3DOT	EI6 4DOT
Na	0.01	0.00	0.00	0.01
Fe	5.10	3.63	3.37	5.04
K	0.01	0.01	0.01	0.27
Mg	4.84	6.16	6.00	2.78
Ti	0.00	0.01	0.00	0.00
Si	6.22	6.51	5.95	6.44
Al	3.67	3.40	4.43	4.73
Mn	0.06	0.03	0.03	0.04
Ca	0.02	0.02	0.02	0.01
Ni	0.01	0.02	0.01	0.01
P	0.00	0.00	0.00	0.00
Cr	0.00	0.01	0.01	0.00
Fe/Mg	1.05	0.59	0.56	1.82
Fe/Fe+Mg	0.51	0.37	0.36	0.64
Mg/Fe+Mg	0.49	0.63	0.64	0.36
Al/(Al+Fe+Mg)	0.27	0.26	0.32	0.38

	EI6 5DOT	EI6 #6	EI6 #7	EI6 #8
Na	0.00	0.00	0.00	0.00
Fe	3.15	3.33	5.45	3.13
K	0.01	0.01	0.00	0.01
Mg	6.13	5.98	4.16	6.17
Ti	0.00	0.00	0.00	0.00
Si	6.15	6.06	6.35	6.06
Al	4.21	4.32	3.76	4.33
Mn	0.03	0.02	0.05	0.02
Ca	0.03	0.01	0.01	0.02
Ni	0.02	0.02	0.00	0.02
P	0.00	0.00	0.00	0.00
Cr	0.01	0.01	0.00	0.01
Fe/Mg	0.51	0.56	1.31	0.51
Fe/Fe+Mg	0.34	0.36	0.57	0.34
Mg/Fe+Mg	0.66	0.64	0.43	0.66
Al/(Al+Fe+Mg)	0.31	0.32	0.28	0.32

	EI6 #9	EI6 #10
Na	0.01	0.01
Fe	2.89	3.00
K	0.00	0.01
Mg	6.38	6.62
Ti	0.00	0.00
Si	6.40	6.39
Al	3.90	3.67
Mn	0.02	0.03
Ca	0.02	0.02
Ni	0.01	0.02
P	0.00	0.00
Cr	0.01	0.00
Fe/Mg	0.45	0.45
Fe/Fe+Mg	0.31	0.31
Mg/Fe+Mg	0.69	0.69
Al/(Al+Fe+Mg)	0.30	0.28

CHLORITE DATA IRISHTOWN

	IR11 2DOT	IR11 3DOT	IR11 4DOT	IR11 5DOT	IR11 6DOT	IR11 7DOT	IR11 8DOT	IR11 9DOT	IR11 10DOT	IR11 11DOT
Na_2O	0.015	0.000	0.032	0.000	0.000	0.000	0.062	0.000	0.000	0.000
FeO	30.609	29.952	27.295	28.971	29.633	30.414	27.717	30.865	29.348	30.772
K_2O	0.000	0.224	1.370	0.007	0.393	0.028	0.797	0.021	0.390	0.082
MgO	9.360	9.298	8.458	10.460	8.503	9.884	8.938	9.592	9.241	10.111
TiO_2	0.012	0.106	0.063	0.000	0.000	0.000	0.008	0.061	0.026	0.074
SiO_2	23.993	24.618	27.073	24.634	25.052	23.105	25.527	24.033	24.730	24.064
Al_2O_3	22.616	22.534	23.880	23.457	21.634	24.243	23.846	22.656	22.457	23.253
MnO	0.078	0.082	0.107	0.113	0.073	0.103	0.070	0.040	0.115	0.138
CaO	0.016	0.000	0.008	0.000	0.000	0.001	0.019	0.009	0.000	0.000
NiO	0.012	0.054	0.015	0.049	0.041	0.045	0.035	0.013	0.030	0.000
P_2O_5	0.000	0.000	0.000	0.023	0.000	0.019	0.000	0.001	0.000	0.000
Cr_2O_3	0.043	0.027	0.062	0.030	0.008	0.027	0.053	0.039	0.011	0.002
TOTAL	86.754	86.895	88.363	87.744	85.337	87.869	87.072	87.330	86.348	88.496

	IRI1 2DOT	IRI1 3DOT	IRI1 4DOT	IRI1 5DOT
Na	0.01	0.00	0.01	0.00
Fe	5.61	5.46	4.81	5.19
K	0.00	0.06	0.37	0.00
Mg	3.06	3.02	2.65	3.34
Ti	0.00	0.02	0.01	0.00
Si	5.26	5.37	5.70	5.27
Al	5.84	5.79	5.93	5.92
Mn	0.01	0.02	0.02	0.02
Ca	0.00	0.00	0.00	0.00
Ni	0.00	0.01	0.00	0.01
P	0.00	0.00	0.00	0.00
Cr	0.01	0.00	0.01	0.01
Fe/Mg	1.83	1.81	1.81	1.55
Fe/Fe+Mg	0.65	0.64	0.64	0.61
Mg/Fe+Mg	0.35	0.36	0.36	0.39
Al/(Al+Fe+Mg)	0.40	0.41	0.44	0.41

	IRI1 6DOT	IRI1 7DOT	IRI1 8DOT	IRI1 9DOT
Na	0.00	0.00	0.03	0.00
Fe	5.50	5.50	4.97	5.63
K	0.11	0.01	0.22	0.01
Mg	2.81	3.19	2.86	3.12
Ti	0.00	0.00	0.00	0.01
Si	5.56	5.00	5.48	5.24
Al	5.66	6.18	6.03	5.82
Mn	0.01	0.02	0.01	0.01
Ca	0.00	0.00	0.00	0.00
Ni	0.01	0.01	0.01	0.00
P	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.01	0.01
Fe/Mg	1.96	1.73	1.74	1.81
Fe/Fe+Mg	0.66	0.63	0.64	0.64
Fe+Mg	0.34	0.37	0.36	0.36
Al/(Al+Fe+Mg)	0.41	0.42	0.44	0.40

	IRI1 10DOT	IRI1 11DOT
Na	0.00	0.00
Fe	5.37	5.53
K	0.11	0.02
Mg	3.02	3.24
Ti	0.00	0.01
Si	5.41	5.17
Al	5.79	5.89
Mn	0.02	0.03
Ca	0.00	0.00
Ni	0.01	0.00
P	0.00	0.00
Cr	0.00	0.00
Fe/Mg	1.78	1.71
Fe/Fe+Mg	0.64	0.63
Mg/Fe+Mg	0.36	0.37
Al/(Al+Fe+Mg)	0.41	0.40

A 3.7

Goose Tickle Chromite

	ML12	ML12	ML12	ML12	ML12
	CORE	RIM		CORE	RIM
AL203	31.87	31.67	22.66	18.71	18.32
TI02	0.5	0.5	0.02	0.04	0.05
MGO	14.06	11.26	13.67	10.85	10.69
FEO	21.77	22.01	19.57	18.57	18.65
MNO	0.27	0.18	0.29	0.36	0.38
NiO	0.19	0.06	0.12	0.05	0
CR203	32.41	31.9	43.61	51.24	51.44
V 205	0.01	0.01	0.01	0.01	0.01
TOTAL	101.08	97.59	99.95	99.83	99.54

	PCF1	PCF1	PCI	PCI	PCI
			CORE	RIM	
AL203	29.34	36.4	23.56	23.49	34.45
TI02	0.31	0.07	0	0.02	0.13
MGO	13.56	16.69	13.77	13.6	12.46
FEO	21.44	13.41	15.61	15.71	23.12
MNO	0.27	0.19	0.19	0.17	0.33
NiO	0.22	0.13	0.09	0.1	0.07
CR203	33.99	33.98	46.85	46.86	28.89
V 205	0.01	0	0	0.01	0.01
TOTAL	99.14	100.87	100.07	99.96	99.46

	PCI	PCI CHLORITE CORE	ML19	ML19	TRC4
AL203	15.86	16.96	26.91	14.23	32.17
TI02	0.08	0.01	0.05	0.93	0.15
MGO	8.61	11.25	13.54	7.48	13.98
FEO	26.86	18.7	18.21	27.96	21.33
MNO	0.4	0.33	0.3	0.34	0.28
NiO	0.07	0.07	0.05	0.05	0.06
CR203	47.03	53.65	40.33	47.09	33.09
V 205	0.01	0.01	0.01	0.01	0.01
TOTAL	98.92	100.98	99.4	98.09	101.07

	TRC4
AL203	13.79
TI02	0.06
MGO	8.84
FEO	22.47
MNO	0.45
NiO	0
CR203	54.77
V 205	0.01
TOTAL	100.39

American Tickle Feldspars

	BA4 KSP1	BA4 KSP2	BA4 KSP3
Na2O	0.427	0.513	1.292
Fe2O3	0.199	0.208	0.188
K2O	16.33	16.215	14.635
Al2O3	18.848	18.76	19.132
TiO2	0	0	0
SiO2	64.678	65.312	64.728
MgO	0	0	0
MnO	0.029	0.034	0.027
CaO	0.024	0	0.062
BaO	0.356	0.402	0.868
SrO	0	0.112	0.111
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.891	101.556	101.043

	BA4 PL1	BA4 PL2	BA4 PL3
Na2O	8.742	11.419	11.248
Fe2O3	0.242	0.288	0.313
K2O	0.368	0.418	0.081
Al2O3	24.076	20.736	20.29
TiO2	0.052	0.014	0
SiO2	62.432	68.557	68.133
MgO	0	0.134	0.006
MnO	0	0.001	0.036
CaO	4.805	0.023	0.547
BaO	0	0.026	0.019
SrO	0.051	0.038	0.049
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.768	101.654	100.722

	BA4 PL4	BA4 PL5	BA4 PL6
Na2O	10.284	11.74	8.757
Fe2O3	0.162	0.058	0.099
K2O	0.477	0.097	0.194
Al2O3	22.787	20.165	24.008
TiO2	0.022	0.042	0.001
SiO2	65.849	68.889	62.002
MgO	0.012	0	0
MnO	0	0	0
CaO	2.037	0.041	4.722
BaO	0	0.07	0.058
SrO	0.078	0.027	0.141
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.708	101.129	99.982

	PC1-1 KSP1	PC1-1 KSP2	PC1-1 KSP3
Na2O	0.416	0.278	0.394
Fe2O3	0.088	0.246	0.187
K2O	16.388	16.771	15.87
Al2O3	18.906	18.894	18.924
TiO2	0	0.041	0
SiO2	65.14	64.362	63.737
MgO	0	0	0.007
MnO	0	0	0
CaO	0.001	0.03	0.024
BaO	0.217	0.113	1.052
SrO	0	0	0.016
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.156	100.735	100.211

	PC1-1 KSP4	PC1-1 PL1	PC1-1 PL2
Na2O	0.256	9.251	11.574
Fe2O3	0.07	0.154	0.115
K2O	16.614	0.078	0.02
Al2O3	18.788	23.441	19.967
TiO2	0	0.042	0.034
SiO2	64.743	63.597	68.546
MgO	0	0	0
MnO	0	0.002	0.037
CaO	0.024	4.115	0.056
BaO	0.23	0.011	0.021
SrO	0.027	0.164	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.752	100.855	100.37

	PC1-1 PL3	PC1-1 PL4	PC1-1 PL5
Na2O	9.589	10.805	11.596
Fe2O3	0.668	0.468	0.167
K2O	1.853	0.387	0.117
Al2O3	22.877	20.797	20.08
TiO2	0	0	0
SiO2	64.938	67.628	69.431
MgO	0.352	0.205	0
MnO	0.014	0.015	0.007
CaO	0.741	0.564	0.064
BaO	0.101	0.037	0.109
SrO	0.129	0.014	0.054
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.262	100.92	101.625

American Tickle Feldspars

	PC1-1 PL6	PC1-1 PL6	PC1-1 PL7
Na2O	8.172	11.875	2.464
Fe2O3	0.104	0.113	0.042
K2O	0.186	0.027	0.012
Al2O3	24.935	20.016	3.552
TiO2	0	0	0
SiO2	61.693	68.724	12.332
MgO	0	0	0
MnO	0.001	0.026	0
CaO	5.853	0.082	0.006
BaO	0	0.022	0.012
SrO	0.083	0	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.027	100.885	18.42

	TCA12 KSP1	TCA12 LSP2	TCA12 KSP3
Na2O	1.237	0.303	0.842
Fe2O3	0.034	0.074	0.053
K2O	14.764	16.486	15.496
Al2O3	19.114	18.763	18.989
TiO2	0	0	0
SiO2	63.241	64.396	64.043
MgO	0	0	0
MnO	0.008	0.008	0
CaO	0	0	0.005
BaO	1.142	0.265	0.519
SrO	0.207	0	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	99.747	100.295	99.947

	TCA12 KSP4	TCA12 PL1	TCA12 PL2
Na2O	0.712	11.565	11.355
Fe2O3	0.031	0.365	0.029
K2O	15.816	0.047	0.163
Al2O3	18.731	20.061	20.072
TiO2	0	0	0
SiO2	64.695	69.092	68.882
MgO	0	0	0.015
MnO	0	0	0
CaO	0.013	0.184	0.028
BaO	0.101	0.017	0.075
SrO	0.041	0.011	0.04
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.14	101.342	100.659

American Tickle Feldspars

	TCA12 PL3	TCA12 PL4	TCA12 PL5
Na2O	9.632	9.187	11.67
Fe2O3	0.095	0.095	0.209
K2O	0.153	0.09	0.056
Al2O3	22.68	23.4	19.926
TiO2	0	0	0.008
SiO2	64.088	63.595	69.039
MgO	0	0	0
MnO	0.042	0	0.008
CaO	3.136	4.193	0.114
BaO	0.002	0.06	0.064
SrO	0.03	0.066	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	99.858	100.686	101.094

	TCA12 PL6
Na2O	8.769
Fe2O3	0.141
K2O	0.219
Al2O3	24.116
TiO2	0.037
SiO2	63.081
MgO	0
MnO	0
CaO	4.689
BaO	0.028
SrO	0.073
FeO	na
NiO	na
Cr2O3	na
TOTAL	101.153

Mainland Feldspars

	TRC A28KSP1	TRC A28KSP2	TRC A28KSP3
Na2O	0.712	0.337	11.24
Fe2O3	0.044	0.041	0
K2O	15.677	16.261	0.4
Al2O3	18.67	18.512	19.881
TiO2	0	0	0.021
SiO2	64.947	64.346	69.057
MgO	0.004	0	0.003
MnO	0	0	0
CaO	0.048	0.008	0.309
BaO	0.332	0.136	0.031
SrO	0.024	0.04	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.458	99.681	100.942

	TRC A28KSP4	TRC A28PL1	TRC A28PL2
Na2O	0.676	11.856	11.418
Fe2O3	0.013	0.016	0.022
K2O	15.82	0.059	0.024
Al2O3	18.874	19.691	19.776
TiO2	0	0	0
SiO2	64.941	68.463	68.768
MgO	0	0.004	0
MnO	0	0	0.003
CaO	0.009	0.136	0.196
BaO	0.452	0	0.06
SrO	0.068	0.088	0.019
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.853	100.313	100.286

	TRC A28PL3	TRC A28PL4	TRC A28PL5
Na2O	11.715	11.903	11.395
Fe2O3	0.076	0.008	0.182
K2O	0.014	0.023	0.087
Al2O3	19.795	19.887	20.71
TiO2	0.009	0	0
SiO2	70.164	68.695	66.911
MgO	0	0	0.005
MnO	0.001	0.033	0.002
CaO	0.05	0.072	0.731
BaO	0.005	0	0.007
SrO	0	0.005	0.1
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.829	100.626	100.13

Mainland Feldspars

	TRC-1KSP1	TRC-1KSP2	TRC-1KSP3
Na2O	1.237	1.441	0.037
Fe2O3	0.158	0.062	0.025
K2O	15.068	14.823	16.679
Al2O3	18.601	18.525	18.784
TiO2	0.005	0	0.015
SiO2	64.662	64.649	63.854
MgO	0	0	0.037
MnO	0.008	0.024	0.026
CaO	0	0.041	0.04
BaO	0.02	0.24	0
SrO	0.018	0.024	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	99.777	99.829	99.497

	TRC-1KSP4	TRC-1PL1	TRC-1PL2
Na2O	0.271	11.802	11.709
Fe2O3	0	0.098	0.1
K2O	16.658	0.018	0.03
Al2O3	18.725	20.326	19.916
TiO2	0.041	0.012	0
SiO2	64.317	67.823	68.978
MgO	0	0	0.007
MnO	0	0.038	0.019
CaO	0.019	0.209	0.124
BaO	0.358	0.055	0.054
SrO	0.004	0.1	0.024
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.393	100.481	100.961

	TRC-1PL3	TRC-1PL3	TRC-1PL4
	CORE	RIM	LAMEL
Na2O	8.707	11.262	11.516
Fe2O3	0.069	0.009	0.003
K2O	0.182	0.035	0.098
Al2O3	24.109	19.829	19.753
TiO2	0.055	0.042	0.026
SiO2	61.657	67.868	68.83
MgO	0	0	0
MnO	0.025	0	0
CaO	4.787	0.377	0.129
BaO	0.009	0	0.065
SrO	0.021	0.042	0.016
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	99.621	99.464	100.436

Mainland Feldspars

	TRC-1PL4	TRC-1PL5	TRC-1PL6
Na2O	0.358	9.404	11.459
Fe2O3	0	0.153	0.042
K2O	16.611	0.151	0.063
Al2O3	18.812	22.871	20.159
TiO2	0	0	0.024
SiO2	63.953	63.756	67.42
MgO	0	0	0
MnO	0.053	0	0.005
CaO	0.037	3.832	0.305
BaO	0.084	0.014	0.083
SrO	0	0.144	0.068
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	99.908	100.325	99.628

	TRC A10	TRC A10	TRC A10
Na2O	0.85	9.43	8.94
Fe2O3	na	na	na
K2O	15.47	0.29	0.22
Al2O3	18.31	22.81	22.25
TiO2	0	0.02	0
SiO2	65.81	64.52	64.73
MgO	0.01	0	0
MnO	0.01	0	0.03
CaO	0.02	4.33	4.08
BaO	na	na	na
SrO	na	na	na
FeO	0.07	0.1	0.07
NiO	0	na	na
Cr2O3	0.07	na	na
TOTAL	100.62	101.5	100.3[illegible]

	TRC A10	TRC A10	TRC A10
Na2O	0.52	1.09	10.27
Fe2O3	na	na	na
K2O	16.19	14.82	0.05
Al2O3	17.73	17.92	20.61
TiO2	0	0	0
SiO2	64.27	65.81	73.45
MgO	0	0.01	0.2
MnO	0	0.02	0.03
CaO	0.04	0	0.54
BaO	na	na	na
SrO	na	na	na
FeO	0	0.06	0.25
NiO	0.04	0	0
Cr2O3	0	0	0
TOTAL	98.79	99.73	105.4

Mainland Feldspars

	TRC A10	TRC A10	TRC A10
Na2O	0.63	10.65	0.88
Fe2O3	na	na	na
K2O	17.5	0.57	16.72
Al2O3	17.51	20.27	18.32
TiO2	0.02	0.03	0.06
SiO2	64.48	67.54	64.09
MgO	0	0.06	0
MnO	0	0	0
CaO	0	0.59	0
BaO	na	na	na
SrO	na	na	na
FeO	0.06	0.16	0.05
NiO	na	0	na
Cr2O3	na	0	na
TOTAL	100.2	99.87	100.12

	TRC A10	TRC A10	TRC A10
Na2O	0.49	0.39	11.39
Fe2O3	na	na	na
K2O	18.17	16.64	0.13
Al2O3	17.47	18.03	19.07
TiO2	0	0	0.01
SiO2	65.55	64.54	68.68
MgO	0.01	0.01	0
MnO	0	0	0.06
CaO	0.07	0	0.22
BaO	na	na	na
SrO	na	na	na
FeO	0	0.07	0.1
NiO	na	0	0
Cr2O3	na	0	0
TOTAL	101.76	99.68	99.66

	TRC A10	TRC A10	ML24
Na2O	9.18	1.83	0.72
Fe2O3	na	na	na
K2O	0.75	13.95	17.61
Al2O3	21.95	18.73	18.16
TiO2	0.02	0	0.04
SiO2	63.32	66.56	65.4
MgO	0.02	0	0
MnO	0	0	0.01
CaO	2.98	0.02	0.01
BaO	na	na	na
SrO	na	na	na
FeO	0	0.09	0.02
NiO	0	0	na
Cr2O3	0	0	na
TOTAL	98.22	101.18	101.97

Mainland Feldspars

	ML24	ML24	ML24
Na2O	0.05	9.31	0.98
Fe2O3	na	na	na
K2O	18.66	0.21	16.66
Al2O3	17.32	22.29	17.36
TiO2	0	0.02	0.03
SiO2	65.21	64.67	63.32
MgO	0	0.01	0.01
MnO	0.03	0	0.03
CaO	0.06	4.05	0
BaO	na	na	na
SrO	na	na	na
FeO	0.03	0.03	0.03
NiO	na	0	na
Cr2O3	na	0	na
TOTAL	101.36	100.59	98.42

	ML24	ML24	ML24
Na2O	0.51	0.32	0.02
Fe2O3	na	na	na
K2O	17.3	16.05	0
Al2O3	17.71	18.17	14.65
TiO2	0.06	0	0.05
SiO2	63.73	63.98	28.56
MgO	0.02	0	18.34
MnO	0	0	0.05
CaO	0.01	0	0.14
BaO	na	na	na
SrO	na	na	na
FeO	0.06	0.05	20.73
NiO	na	0	na
Cr2O3	na	0.03	na
TOTAL	99.4	98.6	82.54

	ML24
Na2O	11.24
Fe2O3	na
K2O	0.1
Al2O3	20.08
TiO2	0
SiO2	73.86
MgO	0.01
MnO	0
CaO	0.11
BaO	na
SrO	na
FeO	0.01
NiO	0
Cr2O3	0.01
TOTAL	105.42

Lower Head Feldspars

	MPS-23KSP1	MPS-23KSP2	MPS-23KSP3
Na2O	0.833	0.277	0.451
Fe2O3	0.032	0.116	0.082
K2O	15.906	16.498	16.098
Al2O3	18.637	18.887	18.734
TiO2	0	0	0
SiO2	65.122	64.785	64.839
MgO	0	0.001	0
MnO	0.027	0	0.005
CaO	0.056	0	0.001
BaO	0.192	0.862	0.712
SrO	0.036	0.089	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.841	101.515	100.922

	MPS-23KSP4	MPS-23PL1 RIM	MPS-23PL1 RIM2
Na2O	0.334	1.425	10.904
Fe2O3	0.021	1.392	0.71
K2O	16.516	9.789	0.099
Al2O3	18.614	30.755	20.198
TiO2	0	0	0.057
SiO2	65.145	51.687	67.953
MgO	0	1.584	0.038
MnO	0.024	0.006	0
CaO	0	0.093	0.785
BaO	0.209	0.107	0
SrO	0	0.008	0.068
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.863	96.846	100.812

	MPS-23PL2	MPS-23PL3	MPS-23PL4
Na2O	11.424	8.704	11.872
Fe2O3	0.076	0.125	0.065
K2O	0.141	0.335	0.024
Al2O3	20.563	24.463	20.026
TiO2	0	0	0
SiO2	68.644	62.106	70.039
MgO	0	0	0
MnO	0.019	0.006	0.011
CaO	0.576	5.058	0.154
BaO	0.137	0	0.003
SrO	0.176	0.141	0.048
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.756	100.938	102.242

Lower Head Feldspars

	MPS-23PL5	MPS-23PL6	MAP B3KSP1
Na2O	10.776	8.254	0.639
Fe2O3	0.09	0.078	0.082
K2O	1.161	0.231	16.065
Al2O3	19.752	24.254	18.503
TiO2	0	0	0
SiO2	69.47	62.162	63.905
MgO	0	0	0.001
MnO	0	0	0
CaO	0.175	5.491	0.018
BaO	0.014	0	0.169
SrO	0.037	0.074	0.139
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.475	100.544	99.521

	MAP B3KSP2	MAP B3KSP3	MAP B3KSP4
Na2O	1.381	0.495	0.499
Fe2O3	0.183	0.171	0.17
K2O	14.645	16.316	16.103
Al2O3	18.948	18.972	18.641
TiO2	0	0.031	0
SiO2	64.683	65.263	65.231
MgO	0	0	0
MnO	0	0.009	0.044
CaO	0.054	0	0
BaO	0.479	0.355	0.109
SrO	0.099	0.06	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.472	101.672	100.797

	MAP BK3SP5	MAP B3PL1 CORE	MAP B3PL1 RIM
Na2O	0.383	11.764	0.625
Fe2O3	0.126	0.185	0.361
K2O	16.458	0.201	15.891
Al2O3	18.616	20.105	18.619
TiO2	0	0.01	0
SiO2	64.433	68.709	63.691
MgO	0.004	0.013	0.112
MnO	0.005	0.038	0
CaO	0	0.166	0
BaO	0.378	0.025	0.6
SrO	0	0.12	0.099
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.403	101.336	99.998

Lower Head Feldspars

	MAP B3PL2	MAP B3PL3	MAP B3PL4
Na2O	11.358	10.326	9.06
Fe2O3	0.122	0.376	0.203
K2O	0.084	0.74	0.097
Al2O3	20.422	20.338	22.972
TiO2	0	0	0.014
SiO2	68.244	66.352	62.375
MgO	0	0.168	0
MnO	0.018	0.008	0.051
CaO	0.755	0.233	4.11
BaO	0.03	0.05	0.004
SrO	0.103	0	0.031
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.136	98.591	98.917

	MAP B3PL5	WBS B1KSP1	WBS B1KSP2
Na2O	8.562	0.687	1.255
Fe2O3	0.127	0.166	0.102
K2O	0.105	16.197	15.268
Al2O3	24.291	18.91	18.915
TiO2	0.038	0	0
SiO2	61.839	63.585	64.347
MgO	0	0	0
MnO	0.034	0	0.005
CaO	5.142	0	0
BaO	0	0.043	0.148
SrO	0.078	0.042	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.216	99.63	100.04

	WBS B1KSP3	WBS B1KSP4	WBS B1PL1
Na2O	0.196	0.906	9.326
Fe2O3	0.102	0.111	0.14
K2O	16.522	15.799	0.243
Al2O3	18.365	18.711	23.105
TiO2	0	0	0
SiO2	63.95	64.506	62.847
MgO	0	0	0
MnO	0.022	0.05	0.002
CaO	0	0.031	3.843
BaO	0.327	0.067	0.056
SrO	0	0.037	0.22
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	99.484	100.218	99.782

Lower Head Feldspars

	WBS B1PL2	WBS B1PL3	WBS B1PL4
Na2O	11.856	8.555	8.892
Fe2O3	0.077	0.154	0.048
K2O	0.044	0.408	0.094
Al2O3	19.978	24.022	23.74
TiO2	0.036	0	0
SiO2	69.199	62.141	62.708
MgO	0	0.003	0
MnO	0	0.011	0.053
CaO	0.027	4.949	4.556
BaO	0	0.049	0.002
SrO	0	0.181	0.03
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	101.217	100.473	100.123

	WBS B1PL5	WBS B1PL6
Na2O	11.59	11.177
Fe2O3	0.058	0
K2O	0.043	0.208
Al2O3	19.862	20.364
TiO2	0	0.002
SiO2	69.075	66.228
MgO	0	0.009
MnO	0	0.009
CaO	0.12	0.781
BaO	0.058	0
SrO	0.06	0
FeO	na	na
NiO	na	na
Cr2O3	na	na
TOTAL	100.866	98.778

Cambrian Sandstones Feldspars

	BMD2 PL1	BMD2 PL2	BMD2 PL3
Na2O	11.403	11.568	10.826
Fe2O3	0.065	0.071	0.103
K2O	0.053	0.041	0.829
Al2O3	19.694	19.875	21.084
TiO2	0	0	0
SiO2	69.214	69.318	66.777
MgO	0	0	0.017
MnO	0	0.063	0
CaO	0.154	0.129	0.054
BaO	0	0.041	0
SrO	0.014	0.032	0
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	100.597	101.138	99.69

	BMD2 PL4	BMD2 PL5	BMD2 PL6
Na2O	11.376	11.457	11.667
Fe2O3	0.11	0.025	0.035
K2O	0.031	0.069	0.022
Al2O3	19.843	20.038	19.813
TiO2	0	0.024	0
SiO2	68.217	67.656	68.645
MgO	0	0	0
MnO	0.039	0	0.004
CaO	0.076	0.293	0.198
BaO	0.049	0.018	0
SrO	0.073	0.022	0.042
FeO	na	na	na
NiO	na	na	na
Cr2O3	na	na	na
TOTAL	99.814	99.602	100.426

	119-86-2	119-86-2	119-86-2
Na2O	11.45	12.5	0.15
Fe2O3	na	na	na
K2O	0.08	0.05	11.36
Al2O3	19.58	18.81	29.52
TiO2	0.03	0.02	0.33
SiO2	72.29	68.64	49.01
MgO	0	0	1.25
MnO	0.03	0	0.03
CaO	0.16	0.08	0.07
BaO	na	na	na
SrO	na	na	na
FeO	0.01	0.08	4.54
NiO	0.02	na	na
Cr2O3	0	na	na
TOTAL	103.65	100.18	96.26

Cambrian Sandstones Feldspars

	119-86-2	119-86-2	119-86-2
Na2O	11.62	11.31	2.66
Fe2O3	na	na	na
K2O	0.04	0.03	0
Al2O3	19.01	19.52	31.06
TiO2	0	0.02	0.21
SiO2	68.43	70.44	35.68
MgO	0	0	5.72
MnO	0	0	0
CaO	0.04	0.11	0.25
BaO	na	na	na
SrO	na	na	na
FeO	0.16	0.04	9.52
NiO	0	0	na
Cr2O3	0.04	0.05	na
TOTAL	99.34	101.52	85.1

	119-86-2
Na2O	3.11
Fe2O3	na
K2O	13.51
Al2O3	18.57
TiO2	0.05
SiO2	63.95
MgO	0
MnO	0
CaO	0
BaO	na
SrO	na
FeO	0.21
NiO	na
Cr2O3	na
TOTAL	99.4

APPENDIX 4 POINT COUNT DATA

These tables provide raw data and recalculated parameters mostly according to Ingersoll (1990). A key to abbreviations is given in chapter 4, table 4.5.

N=Number of points counted.
C=Amount of cement.
M=Amount of matrix.
A=Number of altered grains.

Other recalculated parameters as in Ingersoll (1990) except for Lph/Lt (phyllosilicate grains/total lithic fragments). See chapter 4 for discussion of this parameter.

Ls=sedimentary rock fragments
Lv=volcanic fragments
Lm=metamorphic fragments
Lt=total lithic fragments
Q=total quartz
F=total feldspar
L=lithic fragments (excluding polycrystalline quartz)
Qm=monocrystalline quartz
P=total plagioclase

American Tickle Point Count Data

	ba3	bib3	tc7	gtb5	bbb4
quartz	163	150	83	97	160
polyqzwfa	0	0	0	1	0
polyqznfa	2	1	2	3	0
plag	43	43	27	41	24
kspar	0	6	11	0	1
monomica	0	1	4	0	0
phyllosil	2	39	32	1	8
opaque	1	0	3	0	0
glauc	0	0	0	0	0
volcglass	1	4	0	0	0
volcaph	1	7	15	4	6
volcmicr	3	10	1	2	3
slate	0	0	2	0	0
semischis	0	0	0	0	0
qfmagg	0	0	0	0	0
polymic	0	0	0	0	0
mudstone	21	19	67	13	43
lamsh	18	4	13	7	7
micrlst	23	15	5	33	2
calcite	0	5	7	9	63
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	45	83	120	165	50
carbcem	72	23	6	14	10
qzcem	2	0	1	3	7
unident	0	0	0	0	0
heavy	0	3	0	1	1
chert	0	0	0	0	0
sltstone	8	0	3	7	2
altk	4	3	9	10	20
N	409	416	411	411	407
M+C	29.10	25.48	30.90	44.28	16.46
M+C+A	29.10	26.68	32.60	46.47	31.94
Ls/Lt	87.04	51.11	80.58	72.97	85.25
Lv/Lt	9.26	46.67	15.53	16.22	14.75
Lm/Lt	3.70	2.22	3.88	10.81	-0.00
Q+F+L	264.00	247.00	233.00	185.00	266.00
Q	62.50	61.13	36.48	54.59	60.15
F	17.80	21.05	20.17	27.57	16.92
L	19.70	17.81	43.35	17.84	22.93
Qm+F+Lt	264.00	247.00	233.00	185.00	266.00
Qm	61.74	60.73	35.62	52.43	60.15
F	17.80	21.05	20.17	27.57	16.92
Lt	20.45	18.22	44.21	20.00	22.93
P/F	0.91	0.83	0.57	0.80	0.53
Lph/Lt	0.04	0.87	0.31	0.03	0.13

American Tickle Point Count Data

	tc3	tca3	tc6	pci2	sb8
quartz	72	191	187	103	73
polyqzwfa	0	0	0	1	0
polyqznfa	0	2	0	1	0
plag	34	14	16	32	35
kspar	4	0	0	0	5
monomica	1	1	0	0	2
phyllosil	10	6	40	2	2
opaque	3	0	0	2	2
glauc	0	0	0	0	0
volcglass	0	0	0	0	0
volcaph	8	16	17	5	3
volcmicr	0	2	2	0	2
slate	0	1	1	1	1
semischis	0	0	0	0	0
qfmagg	0	0	0	0	0
polymic	0	0	0	0	0
mudstone	112	34	30	12	17
lamsh	19	13	7	1	4
micrlst	4	5	1	3	7
calcite	0	34	15	21	28
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	97	49	49	92	180
carbcem	28	11	24	12	10
qzcem	1	7	3	0	3
unident	0	0	0	0	0
heavy	0	0	1	0	0
chert	0	1	0	0	0
sltstone	0	6	4	1	0
altk	13	12	11	20	7
N	406	405	408	309	381
M+C	31.03	16.54	18.63	33.66	50.66
M+C+A	31.03	24.94	22.30	40.45	58.01
Ls/Lt	94.24	72.00	67.21	63.64	77.78
Lv/Lt	5.76	24.00	31.15	22.73	18.52
Lm/Lt	0.00	4.00	1.64	13.64	3.70
Q+F+L	262.00	292.00	275.00	177.00	147.00
Q	27.48	66.10	68.00	59.32	49.66
F	19.47	8.90	9.82	29.38	31.97
L	53.05	25.00	22.18	11.30	18.37
Qm+F+Lt	262.00	292.00	275.00	177.00	147.00
Qm	27.48	65.41	68.00	58.19	49.66
F	19.47	8.90	9.82	29.38	31.97
Lt	53.05	25.68	22.18	12.43	18.37
P/F	0.67	0.54	0.59	0.62	0.74
Lph/Lt	0.07	0.08	0.66	0.09	0.07

American Tickle Point Count Data

	tca16	pcf2	ppb1	lsi1	sab9
quartz	173	146	124	103	144
polyqzwfa	0	0	0	0	0
polyqznfa	3	2	4	1	3
plag	32	59	24	25	32
kspar	11	10	5	4	0
monomica	0	0	0	0	0
phyllosil	14	9	3	8	3
opaque	4	0	1	0	2
glauc	0	0	0	0	0
volcglass	0	0	0	0	0
volcaph	9	4	5	4	3
volcmicr	1	1	2	1	3
slate	0	0	0	0	0
semischis	0	0	0	0	0
qfmagg	0	0	0	0	0
polymic	0	0	0	0	0
mudstone	34	21	42	14	38
lamsh	3	3	28	7	5
micrlst	2	3	1	3	9
calcite	10	10	11	89	10
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	83	27	100	138	123
carbcem	17	99	42	8	9
qzcem	1	1	1	0	2
unident	0	0	0	0	0
heavy	3	0	0	0	0
chert	0	0	0	0	0
sltstone	1	0	3	2	1
altk	5	19	5	11	15
N	406	414	401	418	402
M+C	24.88	30.68	35.66	34.93	33.33
M+C+A	27.34	33.09	38.40	56.22	35.82
Ls/Lt	74.51	77.42	86.90	79.31	83.02
Lv/Lt	19.61	16.13	8.33	17.24	11.32
Lm/Lt	5.88	6.45	4.76	3.45	5.66
Q+F+L	272.00	265.00	242.00	172.00	244.00
Q	64.71	55.85	52.89	60.47	60.25
F	17.65	33.21	14.05	23.26	19.26
L	17.65	10.94	33.06	16.28	20.49
Qm+F+Lt	272.00	265.00	242.00	172.00	244.00
Qm	63.60	55.09	51.24	59.88	59.02
F	17.65	33.21	14.05	23.26	19.26
Lt	18.75	11.70	34.71	16.86	21.72
P/F	0.67	0.67	0.71	0.63	0.68
Lph/Lt	0.27	0.29	0.04	0.28	0.06

American Tickle Point Count Data

	pcf4
quartz	225
polyqzwfa	0
polyqznfa	2
plag	30
kspar	1
monomica	1
phyllosil	9
opaque	1
glauc	0
volcglass	0
volcaph	20
volcmicr	1
slate	0
semischis	0
qfmagg	1
polymic	0
mudstone	25
lamsh	1
micrlst	3
calcite	5
bioclast	0
ooid	0
matrix	37
carbcem	28
qzcem	7
unident	0
heavy	2
chert	0
sltstone	5
altk	18
N	422
M+C	17.06
M+C+A	18.25
Ls/Lt	56.36
Lv/Lt	38.18
Lm/Lt	5.45
Q+F+L	329.00
Q	69.00
F	14.89
L	16.11
Qm+F+Lt	329.00
Qm	68.39
F	14.89
Lt	16.72
P/F	0.61
Lph/Lt	0.16

Mainland Formation Point Count Data

	m1b7	m1a14	m125	m1b8	m118
quartz	101	97	165	103	131
polyqzwfa	0	0	0	0	0
polyqznfa	2	6	3	3	2
plag	23	28	24	47	20
kspar	1	11	1	0	0
monomica	0	8	0	0	1
phyllosil	31	47	10	36	42
opaque	2	11	0	1	1
glauc	1	0	1	0	0
volcglass	0	0	1	3	0
volcaph	10	9	3	3	3
volcmicr	1	1	1	1	4
slate	0	1	0	1	0
semischis	0	0	0	0	0
qfmagg	0	0	1	0	0
polymic	0	0	0	0	0
mudstone	78	64	27	53	41
lamsh	25	3	1	0	15
micrlst	4	25	2	6	9
calcite	6	5	0	1	1
bioclast	0	0	0	0	0
ooid	1	0	0	0	0
matrix	61	55	13	51	26
carbcem	27	16	84	63	36
qzcem	11	5	0	5	2
unident	1	1	1	1	0
heavy	0	0	0	0	1
chert	0	0	1	1	1
sltstone	3	0	1	0	5
altk	15	17	23	24	16
N	404	410	363	403	357
M+C	24.50	18.54	26.72	29.53	17.93
M+C+A	25.99	19.76	26.72	29.78	18.21
Ls/Lt	89.08	79.76	76.92	83.08	87.32
Lv/Lt	9.24	11.90	12.82	10.77	9.86
Lm/Lt	1.68	8.33	10.26	6.15	2.82
Q+F+L	259.00	237.00	252.00	239.00	233.00
Q	39.77	43.46	66.67	44.35	55.88
F	15.06	23.63	19.05	29.71	15.13
L	45.17	32.91	14.29	25.94	28.99
Qm	39.00	40.93	65.48	43.10	55.04
F	15.06	23.63	19.05	29.71	15.13
Lt	45.95	35.44	15.48	27.20	29.83
P/F	0.59	0.50	0.50	0.66	0.56
Lph/Lt	0.26	0.56	0.26	0.55	0.59

Mainland Formation Point Count Data

	ml15	ml21	ml20	ml1b2	ml22
quartz	103	174	149	171	176
polyqzwfa	0	0	1	0	0
polyqznfa	1	1	6	4	2
plag	56	24	34	23	24
kspar	7	0	0	0	0
monomica	0	0	0	1	0
phyllosil	32	25	19	23	19
opaque	12	2	1	4	1
glauc	0	0	0	0	0
volcglass	0	0	0	3	0
volcaph	3	8	8	16	10
volcmicr	1	5	1	6	2
slate	0	0	0	0	0
semischis	0	0	0	0	0
qfmagg	0	0	1	0	0
polymic	0	0	0	0	0
mudstone	34	57	63	32	46
lamsh	0	1	12	11	1
micrlst	5	2	0	4	1
calcite	2	1	0	13	5
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	82	31	21	42	16
carbcem	74	61	58	18	78
qzcem	0	1	5	3	4
unident	0	0	0	0	1
heavy	1	0	0	0	0
chert	0	0	2	3	5
sltstone	0	0	3	1	2
altk	7	20	16	11	13
N	420	413	400	389	406
M+C	37.14	22.52	21.00	16.20	24.14
M+C+A	37.62	22.76	21.00	19.54	25.37
Ls/Lt	87.18	80.56	82.47	61.84	79.41
Lv/Lt	10.26	18.06	9.28	32.89	17.65
Lm/Lt	2.56	1.39	8.25	5.26	2.94
Q+F+L	212.00	290.00	296.00	281.00	281.00
Q	49.06	60.34	52.70	62.28	63.35
F	33.02	15.17	16.89	12.10	13.17
L	17.92	24.48	30.41	25.62	23.49
Qm	48.58	60.00	50.34	60.85	62.63
F	33.02	15.17	16.89	12.10	13.17
Lt	18.40	24.83	32.77	27.05	24.20
P/F	0.80	0.55	0.68	0.68	0.65
Lph/Lt	0.32	0.35	0.20	0.30	0.28

Mainland Formation Point Count Data

	ml23	mla10	trca5	trc5	trca25
quartz	192	127	198	139	154
polyqzwfa	0	0	0	0	0
polyqznfa	0	2	2	1	2
plag	27	15	23	42	22
kspar	0	0	1	10	8
monomica	1	0	0	1	0
phyllosil	4	50	46	30	24
opaque	1	1	2	5	0
glauc	0	0	0	0	0
volcglass	1	1	0	0	0
volcaph	15	3	7	17	8
volcmicr	0	2	5	8	8
slate	3	0	1	1	1
semischis	0	0	0	0	0
qfmagg	1	0	0	0	0
polymic	0	0	0	0	0
mudstone	15	44	38	57	32
lamsh	1	12	8	9	9
micrlst	2	4	9	1	4
calcite	0	14	27	23	12
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	4	85	13	46	53
carbcem	111	15	6	15	52
qzcem	0	14	12	4	6
unident	0	1	0	0	0
heavy	0	0	0	0	0
chert	2	0	1	0	0
sltstone	0	2	7	1	2
altk	20	13	11	6	12
N	400	405	417	416	409
M+C	28.75	28.15	7.43	15.63	27.14
M+C+A	28.75	31.60	13.91	21.15	30.07
Ls/Lt	47.37	87.88	78.26	71.28	69.35
Lv/Lt	42.11	9.09	17.39	26.60	25.81
Lm/Lt	10.53	3.03	4.35	2.13	4.84
Q+F+L	277.00	221.00	302.00	291.00	258.00
Q	69.31	58.37	66.23	48.11	60.47
F	16.97	12.67	11.59	19.93	16.28
L	13.72	28.96	22.19	31.96	23.26
Qm	69.31	57.47	65.56	47.77	59.69
F	16.97	12.67	11.59	19.93	16.28
Lt	13.72	29.86	22.85	32.30	24.03
P/F	0.57	0.54	0.66	0.72	0.52
Lph/Lt	0.11	0.76	0.67	0.32	0.39

Mainland Formation Point Count Data

	trca21
quartz	163
polyqzwfa	0
polyqznfa	3
plag	32
kspar	1
monomica	0
phyllosil	25
opaque	3
glauc	0
volcglass	0
volcaph	9
volcmicr	3
slate	4
semischis	0
qfmagg	0
polymic	0
mudstone	71
lamsh	5
micrlst	9
calcite	7
bioclast	0
ooid	0
matrix	46
carbcem	7
qzcem	0
unident	0
heavy	0
chert	0
sltstone	2
altk	20
N	410
M+C	12.93
M+C+A	14.63
Ls/Lt	80.41
Lv/Lt	12.37
Lm/Lt	7.22
Q+F+L	313.00
Q	53.04
F	16.93
L	30.03
Qm	52.08
F	16.93
Lt	30.99
P/F	0.60
Lph/Lt	0.26

Lower Head Formation Point Count Data

	mpn7b	mpn5b	mpn5a	mpn12	mapb10
quartz	130	139	114	193	167
polyqzwfa	0	0	0	0	0
polyqznfa	0	0	0	0	1
plag	50	53	73	32	63
kspar	0	0	0	2	0
monomica	0	0	1	0	3
phyllosil	41	20	32	16	9
opaque	4	4	7	3	5
glauc	0	0	0	0	0
volcglass	0	1	0	1	0
volcaph	4	6	7	16	22
volcmicr	5	2	2	4	3
slate	1	1	0	2	0
semischis	0	0	0	0	0
qfmagg	1	0	0	0	0
polymic	0	0	0	0	0
mudstone	17	28	15	8	10
lamsh	5	2	1	2	0
micrlst	1	5	5	4	3
calcite	0	1	0	4	1
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	72	45	131	77	67
carbcem	7	49	2	21	32
qzcem	1	0	10	4	13
unident	0	0	0	0	0
heavy	0	0	0	0	0
chert	1	0	1	0	1
sltstone	0	0	1	2	1
altk	12	25	3	23	15
N	352	381	405	414	416
M+C	22.73	24.67	35.31	24.64	26.92
M+C+A	22.73	24.93	35.31	25.60	27.16
Ls/Lt	67.65	75.00	66.67	34.29	31.58
Lv/Lt	26.47	22.50	33.33	60.00	65.79
Lm/Lt	5.88	2.50	-0.00	5.71	2.63
Q+F+L	226.00	257.00	217.00	285.00	283.00
Q	57.52	54.09	52.53	67.72	59.36
F	27.43	30.35	35.02	20.00	27.56
L	15.04	15.56	12.44	12.28	13.07
Qm	57.52	54.09	52.53	67.72	59.01
F	27.43	30.35	35.02	20.00	27.56
Lt	15.04	15.56	12.44	12.28	13.43
P/F	0.81	0.68	0.96	0.56	0.81
Lph/Lt	1.21	0.50	1.19	0.46	0.24

Lower Head Formation Point Count Data

	port2	lhnb4	mps11	wbna15	wbs1
quartz	226	135	191	199	179
polyqzwfa	0	0	0	1	0
polyqznfa	2	0	3	1	1
plag	30	66	47	35	46
kspar	0	0	4	2	0
monomica	0	1	1	2	1
phyllosil	3	22	6	6	14
opaque	1	4	1	4	1
glauc	0	0	0	1	0
volcglass	0	2	0	0	0
volcaph	13	9	7	7	2
volcmicr	4	4	6	1	8
slate	1	11	0	0	0
semischis	0	0	0	0	0
qfmagg	0	0	0	0	0
polymic	0	0	0	0	0
mudstone	11	10	31	14	14
lamsh	1	4	3	6	1
micrlst	10	3	8	0	4
calcite	6	2	4	10	2
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	25	63	66	73	80
carbcem	36	57	9	17	9
qzcem	0	0	4	2	0
unident	0	0	0	0	0
heavy	0	0	1	0	0
chert	1	1	0	[illegible]	0
sltstone	5	0	4	2	2
altk	25	16	21	17	15
N	400	410	417	400	379
M+C	15.25	29.27	18.94	23.00	23.48
M+C+A	16.75	29.76	19.90	25.50	24.01
Ls/Lt	47.37	36.59	70.37	68.75	60.71
Lv/Lt	44.74	36.59	24.07	25.00	35.71
Lm/Lt	7.89	26.83	5.56	6.25	3.57
Q+F+L	319.00	258.00	317.00	285.00	268.00
Q	71.47	52.33	61.20	70.53	67.16
F	17.24	31.78	22.71	18.95	22.76
L	11.29	15.89	16.09	10.53	10.07
Qm	70.85	52.33	60.25	69.82	66.79
F	17.24	31.78	22.71	18.95	22.76
Lt	11.91	15.89	17.03	11.23	10.45
P/F	0.55	0.80	0.65	0.65	0.75
Lph/Lt	0.08	0.54	0.11	0.19	0.50

Lower Head Formation Point Count Data

	wbn3	rpa10	rpa5	ph4	lhsb6
quartz	138	119	95	215	159
polyqzwfa	0	0	0	0	0
polyqznfa	1	0	0	3	3
plag	49	41	41	29	52
kspar	0	1	5	2	0
monomica	2	2	0	0	1
phyllosil	11	11	20	4	12
opaque	1	1	3	0	5
glauc	0	0	1	0	0
volcglass	0	0	0	1	0
volcaph	5	10	7	14	3
volcmicr	3	1	0	5	6
slate	0	0	1	1	0
semischis	0	0	0	0	0
qfmagg	0	0	0	0	0
polymic	0	0	0	0	0
mudstone	16	23	30	20	32
lamsh	9	2	3	3	6
micrlst	1	0	2	6	4
calcite	2	0	4	12	4
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	50	74	60	31	74
carbcem	94	5	124	39	25
qzcem	0	1	0	3	0
unident	0	0	0	0	0
heavy	1	0	0	0	0
chert	0	0	0	0	0
sltstone	0	2	0	0	1
altk	19	17	10	21	16
N	402	310	406	409	403
M+C	35.82	25.81	45.32	17.85	24.57
M+C+A	36.32	25.81	46.31	20.78	25.56
Ls/Lt	73.53	71.05	80.49	48.94	76.47
Lv/Lt	23.53	28.95	17.07	42.55	17.65
Lm/Lt	2.94	0.00	2.44	8.51	5.88
Q+F+L	240.00	216.00	192.00	314.00	278.00
Q	57.92	55.09	49.48	69.43	58.27
F	28.33	27.31	29.17	16.56	24.46
L	13.75	17.59	21.35	14.01	17.27
Qm	57.50	55.09	49.48	68.47	57.19
F	28.33	27.31	29.17	16.56	24.46
Lt	14.17	17.59	21.35	14.97	18.35
P/F	0.72	0.69	0.73	0.56	0.76
Lph/Lt	0.32	0.29	0.49	0.09	0.24

Lcwer Head Formation Point Count Data

	mapb1	ei2	portb2
quartz	185	109	185
polyqzwfa	0	0	0
polyqznfa	2	0	0
plag	64	40	45
kspar	0	1	14
monomica	0	1	0
phyllosil	4	5	12
opaque	2	9	1
glauc	0	0	0
volcglass	0	0	0
volcaph	6	1	3
volcmicr	1	2	1
slate	0	2	0
semischis	0	0	0
qfmagg	0	0	0
polymic	0	0	0
mudstone	32	40	20
lamsh	5	17	3
micrlst	3	5	7
calcite	0	0	3
bioclast	0	0	0
ooid	0	0	0
matrix	90	149	42
carbcem	13	10	65
qzcem	7	9	3
unident	0	0	1
heavy	0	0	0
chert	0	0	0
sltstone	0	1	0
altk	0	10	10
N	414	411	415
M+C	26.57	40.88	26.51
M+C+A	26.57	40.88	27.23
Ls/Lt	80.43	92.06	85.19
Lv/Lt	15.22	4.76	14.81
Lm/Lt	4.35	3.17	-0.00
Q+F+L	295.00	223.00	281.00
Q	63.39	48.88	65.84
F	21.69	22.87	24.56
L	14.92	28.25	9.61
Qm	62.71	48.88	65.84
F	21.69	22.87	24.56
Lt	15.59	28.25	9.61
P/F	1.00	0.78	0.65
Lph/Lt	0.09	0.08	0.44

Cambrian Sandstones Point Count Data

	bmd5	bmd7	bmd5	wib2	wf7585
quartz	195	183	174	235	172
polyqzwfa	0	0	0	0	0
polyqznfa	2	1	1	1	0
plag	83	65	86	59	94
kspar	0	0	0	0	0
monomica	1	23	2	1	4
phyllosil	6	0	0	0	1
opaque	5	0	2	0	1
glauc	0	0	0	0	1
volcglass	0	0	0	0	0
volcaph	0	0	1	1	0
volcmicr	0	0	0	0	0
slate	0	0	0	0	0
semischis	0	0	0	0	0
qfmagg	0	0	0	0	0
polymic	0	0	0	0	0
mudstone	1	0	0	0	0
lamsh	0	0	0	0	0
micrlst	0	0	0	0	0
calcite	0	0	0	0	2
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	96	135	135	83	97
carbcem	9	0	1	13	34
qzcem	0	1	0	7	2
unident	0	0	0	0	0
heavy	1	0	0	0	0
chert	0	0	0	0	0
sltstone	0	0	0	0	0
altk	2	0	0	0	0
N	401	408	402	400	408
M+C	26.18	33.33	33.83	25.75	32.60
M+C+A	26.18	33.33	33.83	25.75	33.09
Ls/Lt	100.00	0.00	0.00	0.00	0.00
Lv/Lt	0.00	0.00	100.00	100.00	0.00
Lm	0.00	0.00	0.00	0.00	0.00
Q+F+L	282.00	249.00	262.00	296.00	266.00
Q	69.15	73.49	66.41	79.39	64.66
F	30.14	26.10	32.82	19.93	35.34
L	0.71	0.40	0.76	0.68	-0.00
Qm	69.15	73.49	66.41	79.39	64.66
F	30.14	26.10	32.82	19.93	35.34
Lt	0.71	0.40	0.76	0.68	-0.00
P/F	0.98	1.00	1.00	1.00	1.00
Lph/Lt	6.00	0.00	0.00	0.00	0.00

Cambrian Sandstones Point Count Data

	hanb7	mpb5	crog6	sab3	db9
quartz	285	174	134	184	261
polyqzwfa	0	0	0	0	0
polyqznfa	0	1	2	9	0
plag	44	86	63	64	3
kspar	0	0	0	0	11
monomica	0	2	1	0	0
phyllosil	4	0	0	1	1
opaque	3	2	1	4	0
glauc	0	0	0	0	0
volcglass	0	0	0	0	0
volcaph	0	1	1	0	0
volcmicr	0	0	0	0	0
slate	0	0	0	0	0
semischis	0	0	0	0	0
qfmagg	0	0	0	4	0
polymic	0	0	0	0	0
mudstone	1	0	0	2	0
lamsh	0	0	0	0	0
micrlst	0	0	0	1	0
calcite	0	0	0	0	0
bioclast	0	0	0	0	0
ooid	0	0	0	0	0
matrix	55	135	114	143	101
carbcem	0	1	1	0	0
qzcem	20	0	0	0	28
unident	0	0	0	0	0
heavy	0	0	0	0	0
chert	0	0	0	0	0
sltstone	2	0	0	0	0
altk	0	0	0	0	7
N	414	402	317	412	412
M+C	18.12	33.83	36.28	34.71	31.31
M+C+A	18.12	33.83	36.28	34.71	31.31
Ls/Lt	100.00	0.00	0.00	33.33	0.00
Lv/Lt	0.00	100.00	100.00	0.00	0.00
Lm	0.00	0.00	0.00	66.67	0.00
Q+F+L	329.00	262.00	200.00	261.00	282.00
Q	86.63	66.41	67.00	70.50	92.55
F	13.37	32.82	31.50	24.52	7.45
L	-0.00	0.76	1.50	4.98	-0.00
Qm	86.63	66.41	67.00	70.50	92.55
F	13.37	32.82	31.50	24.52	7.45
Lt	-0.00	0.76	1.50	4.98	-0.00
P/F	1.00	1.00	1.00	1.00	0.14
Lph/Lt	1.33	0.00	0.00	0.17	0.00

Cambrian Sandstones Point Count Data

	hb1	gm3	hanb5	iri3
quartz	342	336	135	303
polyqzwfa	0	0	0	0
polyqznfa	1	0	0	0
plag	7	5	80	25
kspar	1	0	0	0
monomica	0	1	1	2
phyllosil	0	0	0	0
opaque	0	1	2	1
glauc	0	0	0	0
volcglass	0	0	0	0
volcaph	0	0	0	0
volcmicr	0	0	0	0
slate	0	0	0	0
semischis	0	0	0	0
qfmagg	0	0	0	0
polymic	0	0	0	0
mudstone	0	0	0	0
lamsh	0	0	1	0
micrlst	0	0	0	0
calcite	0	0	0	0
bioclast	0	0	0	0
ooid	0	0	0	0
matrix	0	6	174	33
carbcem	0	1	5	0
qzcem	39	24	2	35
unident	0	0	1	0
heavy	0	0	1	1
chert	0	0	0	0
sltstone	0	0	0	0
altk	21	26	0	1
N	411	400	402	401
M+C	9.49	7.75	45.02	16.96
M+C+A	9.49	7.75	45.02	16.96
Ls/Lt	0.00	0.00	100.00	0.00
Lv/Lt	0.00	0.00	0.00	0.00
Lm	0.00	0.00	0.00	0.00
Q+F+L	372.00	367.00	215.00	329.00
Q	91.94	91.55	62.79	92.10
F	7.80	8.45	37.21	7.90
L	0.27	0.00	0.00	-0.00
Qm	91.94	91.55	62.79	92.10
F	7.80	8.45	37.21	7.90
Lt	0.27	0.00	0.00	-0.00
P/F	0.24	0.16	1.00	0.96
Lph/Lt	0.00	0.00	0.00	0.00

Miscellaneous Sandstones Point Count Data

	cb9	cb10	nwa10	tpb7
quartz	214	204	131	64
polyqzwfa	2	1	0	0
polyqznfa	0	1	3	1
plag	54	89	42	22
kspar	8	19	8	4
monomica	0	0	2	0
phyllosil	17	2	5	2
opaque	2	0	6	5
glauc	0	0	0	0
volcglass	0	0	0	0
volcaph	16	31	7	8
volcmicr	6	5	4	3
slate	1	0	4	0
semischis	0	0	0	0
qfmagg	1	0	0	0
polymic	0	0	0	0
mudstone	0	3	12	23
lamsh	1	0	0	13
micrlst	2	0	1	17
calcite	0	0	4	36
bioclast	0	0	0	0
ooid	0	0	0	0
matrix	62	26	124	92
carbcem	0	0	38	55
qzcem	2	0	1	0
unident	0	0	0	0
heavy	0	1	0	0
chert	0	0	0	0
sltstone	1	0	0	4
altk	11	18	8	1
N	400	400	400	350
M+C	16.00	6.50	40.75	42.00
M+C+A	16.00	6.50	41.75	52.29
Ls/Lt	7.14	7.32	40.00	76.92
Lv/Lt	78.57	87.80	36.67	21.15
Lm	14.29	4.88	23.33	1.92
Q+F+L	315.00	371.00	219.00	143.00
Q	68.57	55.26	59.82	44.76
F	23.17	33.96	26.48	18.88
L	8.25	10.78	13.70	36.36
Qm	67.94	54.99	59.82	44.76
F	23.17	33.96	26.48	18.88
Lt	8.89	11.05	13.70	36.36
P/F	0.74	0.71	0.72	0.81
Lph/Lt	0.61	0.05	0.17	0.04

APPENDIX 5 BULK GEOCHEMICAL DATA

The majority of the samples (88) in the following data tables were analysed by ACTLABS, Ancaster, Ontario using a combination of Instrumental Neutron Activation Analysis (INAA) (Au, Cr, Ir, Sc, U, Nd, Yb, As, Cs, Mo, Se, W, Sm, Lu, Br, Hf, Rb, Ta, La, Eu, Co, Hg, Sb, Th, Ce, Tb) and all other major and trace elements were analysed by Inductively Coupled Plasma Emission Spectrometry (ICAP) on fused pellets.

For this grade (exploration) analysis ACTLABS quotes precision as plus or minus 100% at detection limits, plus or minus 50% at twice detection limits, and plus or minus 10% at ten times detection limits. Detection limits were quoted as follows (all data are quoted in ppm unless otherwise indicated):

Au (5 ppb), Cr (2), Ir (5 ppb), Sc (0.1), U (0.5), Nd (5), Yb (0.2), As (2), Cs (0.5), Mo (5), Se (3), W (3), Sm (0.1), Lu (0.05), Br (1), Hf (0.5), Rb (20), Ta (1), La (0.5), Eu (0.2), Co (1), Hg (1), Sb (0.2), Th (0.5), Ce (3), Tb (0.5).

Also Ag (0.1), Al2O3 (0.01%), Ba (1), Be (1), Bi (50), Br (1), CaO (0.01%), Cu (1), Fe2O3 (0.01%), K2O (0.03%), MgO (0.01%), Mn (100), Na2O (0.1%), Nb (50), Ni (5), P2O5 (0.01%), Pb (50), SiO2 (0.01%), Sn (50), Sr (1), TiO2 (0.001%), V (3), Y (1), Zn (5), Zr (1).

Total iron is expressed as Fe_2O_3. Data are recalculated to 100% volatile free.

As discussed in chapter 4, samples were contaminated with chromium during the crushing process. Average chromium contamination was 58 ppm for the American Tickle formation, 77 ppm for the Lower Head Formation, and 81 ppm for the Mainland formation. Samples whose Cr values rose (only 2 samples) on the second analysis were not included in the contamination calculation, as the rise was ascribed to inhomogeneity in the sample. Samples for which there was no second analysis available had the appropriate 'contamination factor' subtracted from their original values. These samples were BI B3, PP B1, SAB 3, TCA3, TCA6, TCA12, EI4, MAPB1, MAPB3, RPA2, RPA11, WBSB2, WBNA15, ML11, ML15, TRC A10, TRC A13, TRCA16, TRCA20 (these samples may be marked with an asterisk in some tables).

Nineteen samples were analysed by a combination of other methods. These methods included: XRF analysis of pressed pellets for Co (5ppm), Cr (5ppm), Cu (5ppm), Ni (5ppm), Pb (5ppm), V (5ppm), Zn (5ppm), by ACTLABS; XRF analysis of pressed pellets at Memorial University (other trace elements). Atomic Absorption Analysis (major elements) at Memorial University, and ICP-MS at Memorial University (rare earth elements). Detection limits are quoted in Longerich and Veinott (1986, Memorial University internal report) and details of the ICP-MS method are given in Longerich et al. (1990), and Jenner et al. (1990). Note that high Barium values in several of the samples analysed may render values for Europium suspect. The samples analysed by this combination of techniques were GM1, SAB10, HAS B6, LQ-82-163, BMD 8,

WF-75-85, LQ-83-5A, HB6, MAP B7, LPB1, 239G, HAN B12, LHS B12, RPA 14, ML4, MLB9, DB4, SAINT1, SBB2. (These samples may be marked with a # in some tables).

Some of the major recalculated parameters, particularly Niggli values (after Van de Kemp and Leake 1985) are also provided in these tables. These were the values incorporated into the statistical analyses in appendix 6.

American Tickle Major Elements

	BB B2	BB B4	BB B9	PCF 2
grainsize	f	med/crs	crs	f
structure	lam	x-bed	mass	lam
SiO2	69.27	72.78	77.33	70.53
TiO2	0.55	0.32	0.42	0.39
Al2O3	10.35	5.05	6.66	8.06
Fe2O3	4.87	3.09	3.91	2.92
MnO	0.21	0.40	0.13	0.15
MgO	3.42	3.82	3.29	2.03
CaO	7.09	12.40	5.80	12.05
Na2O	2.08	1.02	1.10	1.96
K2O	2.04	1.08	1.27	1.90
P2O5	0.11	0.05	0.08	0.02
LOI	7.99	12.30	6.21	10.32
analytical total	100.04	99.64	100.66	100.77
al-alk%	11.55	5.18	11.06	6.55
Nig Ti	1.73	0.96	1.72	1.16
Nig Fm	29.46	28.66	35.05	17.03
Nig K	0.39	0.41	0.43	0.39
Nig Mg	0.57	0.68	0.62	0.57
Nig Si	287.15	289.55	417.92	281.88

	PCP B1	PP B1	SPI B1	TC A3
grainsize	crs/vcrs	f/crs	f/med	crs/vcrs
structure	mass	lam/con	rip	x-bed
SiO2	69.01	69.72	58.86	80.89
TiO2	0.45	0.46	0.45	0.22
Al2O3	6.42	9.41	9.71	5.57
Fe2O3	3.40	4.79	6.46	3.47
MnO	0.33	0.13	0.55	0.12
MgO	2.44	4.24	8.61	2.71
CaO	15.37	8.03	11.76	4.97
Na2O	1.61	1.24	1.56	1.06
K2O	0.91	1.91	1.93	0.96
P2O5	0.05	0.07	0.12	0.02
LOI	12.22	9.46	15.70	5.55
analytical total	100.19	100.66	100.87	98.85
al-alk%	5.94	12.60	8.10	10.44
Nig Ti	1.24	1.40	0.91	1.08
Nig Fm	18.85	33.23	42.76	34.70
Nig K	0.27	0.50	0.45	0.37
Nig Mg	0.56	0.63	0.71	0.60
Nig Si	250.08	281.06	159.99	515.33

American Tickle Major Elements

grainsize	TC A6 crs/vcrs	TC A12 med/crs	TC A16 f	BI B3 med
structure	mass	mass	lam	mass
SiO2	79.76	77.24	70.40	68.71
TiO2	0.31	0.40	0.60	0.56
Al2O3	5.49	6.02	10.70	7.79
Fe2O3	3.67	3.57	5.39	5.32
MnO	0.10	0.14	0.06	0.14
MgO	2.87	3.39	5.03	6.23
CaO	5.94	7.04	3.85	9.27
Na2O	0.92	1.08	1.68	1.02
K2O	0.88	1.10	2.15	0.94
P2O5	0.06	0.02	0.13	0.02
LOI	5.88	7.07	6.04	9.43
analytical total	98.67	97.89	100.00	99.12
al-alk%	10.61	9.30	14.36	10.90
Nig Ti	1.40	1.54	1.95	1.52
Nig Fm	34.19	33.68	41.64	41.46
Nig K	0.39	0.40	0.46	0.38
Nig Mg	0.60	0.64	0.65	0.69
Nig Si	475.22	399.03	305.79	249.74

grainsize	BURNT 2 f	GT 1 f	GT B5 crs	GT B10 crs
structure	mass/lam	lam	mass	gr/mass
SiO2	62.67	64.57	68.36	56.08
TiO2	0.65	0.96	0.62	0.57
Al2O3	10.04	11.42	9.78	7.79
Fe2O3	4.08	5.71	4.59	5.25
MnO	0.29	0.33	0.12	0.35
MgO	2.97	4.87	4.20	5.40
CaO	15.18	7.82	8.47	22.46
Na2O	2.46	2.00	1.55	0.87
K2O	1.65	2.21	2.28	1.20
P2O5	0.02	0.11	0.02	0.02
LOI	12.68	9.80	9.87	16.90
analytical total	98.86	100.42	98.57	98.53
al-alk%	7.81	12.03	10.83	7.35
Nig Ti	1.53	2.57	1.80	1.06
Nig Fm	19.51	34.41	31.26	25.45
Nig K	0.31	0.42	0.49	0.48
Nig Mg	0.57	0.61	0.64	0.65
Nig Si	197.01	229.47	263.99	138.15

American Tickle Major Elements

	SB 2	SB B3	SAB 3	LSI 5
grainsize	med	f	f	f
structure	con	lam	lam	lam
SiO2	69.53	55.45	43.37	65.16
TiO2	0.73	0.67	0.29	0.66
Al2O3	12.34	11.31	6.42	10.34
Fe2O3	5.10	4.66	3.71	5.85
MnO	0.05	0.20	0.69	0.11
MgO	3.76	4.63	7.61	6.30
CaO	3.95	18.32	35.09	8.31
Na2O	1.63	3.08	1.78	1.55
K2O	2.32	1.61	1.02	1.70
P2O5	0.08	0.07	0.03	0.02
LOI	5.45	15.75	26.56	8.67
analytical total	99.78	100.45	98.90	98.30
al-alk%	17.32	6.78	2.46	11.99
Nig Ti	2.45	1.29	0.38	1.69
Nig Fm	33.72	22.55	23.34	39.95
Nig K	0.53	0.26	0.27	0.42
Nig Mg	0.59	0.65	0.77	0.68
Nig Si	309.60	141.75	75.99	222.64

	SAB 10	SB B2
grainsize	med/crs	f/med
structure	mass/gr?	lam
SiO2	70.05	41.71
TiO2	0.65	0.34
Al2O3	11.75	6.27
Fe2O3	5.89	3.76
MnO	0.06	0.41
MgO	3.40	10.73
CaO	3.32	34.25
Na2O	1.86	1.31
K2O	2.48	1.07
P2O5	0.08	0.14
LOI	6.31	27.45
analytical total	99.08	98.40
al-alk%	16.66	2.90
Nig Ti	2.29	0.42
Nig Fm	34.64	29.54
Nig K	0.47	0.35
Nig Mg	0.53	0.83
Nig Si	332.22	69.43

American Tickle Trace Elements

Element	BB B2	BB B4	BB B9	PCF 2	PCP B1
Ba	518	263	300	496	302
Sr	205	237	126	166	207
Zr	259	123	181	166	214
Y	24	14	14	12	16
Be	<1	<1	<1	<1	<1
Cu	40	25	20	25	20
Ni	110	110	160	50	180
Pb	<50	<50	<50	<50	<50
V	50	36	42	30	46
Zn	130	80	85	85	75
Ag	1	2.1	0.4	0.3	0.1
Nb	<30	<30	<30	<30	<30
Au	52	78	11	14	14
As	13	14	18	2	7
Br	<1	1	<1	<1	<1
Co	21	9	17	8	15
Cr	330	350	520	180	1100
Cs	2.1	1.2	1.4	<0.5	<0.5
Hf	5.9	2.6	3.8	3.2	4.8
Hg	<1	2	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	72	22	45	59	36
Sb	12	23	5	4	2.9
Sc	8.2	4.4	6.7	4.9	6.1
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	<1	<1
Th	6.4	3.7	4.8	3.6	4.1
U	2.2	0.8	1.2	1.5	1.5
W	<3	<3	<3	<3	<3
La	22.3	12.1	14.4	12.8	13.7
Ce	54	29	37	30	33
Nd	23	14	15	15	15
Sm	4.3	2.4	2.9	2.5	2.7
Eu	0.9	0.5	0.7	0.7	0.6
Tb	0.8	<0.5	<0.5	0.5	0.5
Yb	1.8	1	1.3	1.1	1.2
Lu	0.28	0.14	0.19	0.17	0.22
LaN/YbN	8.17	7.99	7.31	7.67	7.53
La/Yb	12.39	12.10	11.08	11.64	11.42
La/Sm	5.19	5.04	4.97	5.12	5.07
Hf/Yb	3.28	2.60	2.92	2.91	4.00

American Tickle Trace Elements (cont.)

Element	PP B1*	SPI B1	TC A3*	TC A6*	TC A12*
Ba	333	315	311	281	322
Sr	153	104	152	195	165
Zr	187	142	63	81	188
Y	16	18	12	14	16
Be	<1	<1	<1	<1	<1
Cu	30	35	20	70	20
Ni	50	80	170	130	160
Pb	<50	<50	<50	<50	<50
V	54	40	38	42	46
Zn	80	100	110	130	80
Ag	<0.1	0.5	0.4	0.1	0.2
Nb	<30	<30	<30	<30	<30
Au	7	19	17	8	23
As	4	4	9	7	4
Br	<1	<1	<1	<1	<1
Co	12	17	15	21	17
Cr	120	110	370	870	620
Cs	2.1	1.6	<0.5	0.9	<0.5
Hf	4.7	3	1.4	2.4	4.3
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	62	66	32	28	33
Sb	1.6	8.9	5.5	2.3	1.7
Sc	6.8	7.3	5.6	5.9	6.7
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	<1	<1
Th	6.2	5.6	2.7	3.2	3.9
U	2.4	2	1.3	1.1	1.6
W	<3	<3	<3	<3	<3
La	18.7	17	10.2	12.2	14.6
Ce	45	42	24	31	37
Nd	20	16	12	15	18
Sm	3.8	3.7	2.2	3.2	3.1
Eu	0.6	0.7	0.4	0.7	0.8
Tb	0.7	0.6	<0.5	<0.5	0.5
Yb	1.5	1.6	0.8	1	1.3
Lu	0.24	0.25	0.13	0.15	0.18
LaN/YbN	8.22	7.01	8.4	8.05	7.41
La/Yb	12.47	10.63	12.75	12.20	11.23
La/Sm	4.92	4.59	4.64	3.81	4.71
Hf/Yb	3.13	1.88	1.75	2.40	3.31

American Tickle Trace Elements (cont.)

Element	TC A16	BI B3*	BURNT 2	GT 1	GT B5
Ba	505	192	6964	443	407
Sr	116	189	336	228	138
Zr	232	159	203	344	200
Y	18	16	18	26	18
Be	<1	<1	<1	<1	<1
Cu	35	50	25	30	30
Ni	140	260	100	130	40
Pb	<50	<50	<50	<50	<50
V	60	70	56	64	48
Zn	85	95	80	95	75
Ag	<0.1	<0.1	0.4	0.2	0.2
Nb	<30	<30	<30	<30	<30
Au	<5	13	18	21	<5
As	4	9	2	5	2
Br	<1	<1	<1	1	<1
Co	17	34	11	20	9
Cr	300	1440	180	300	130
Cs	2.2	1.7	1.6	3.3	1.9
Hf	5.1	4.1	5.3	8.7	5.2
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	68	21	35	64	64
Sb	1.1	3.6	6.1	4.1	3
Sc	9.5	14	7.5	10	7.6
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	<1	<1
Th	6.8	3.9	5.6	8.4	5.6
U	2.3	1.2	<0.5	2.4	1.5
W	<3	<3	<3	<3	<3
La	20.8	14.8	18.6	27.4	21
Ce	52	34	44	67	50
Nd	23	12	19	25	24
Sm	4	2.5	3.3	5.1	3.9
Eu	0.9	0.6	0.9	1.1	1
Tb	0.6	0.5	0.5	0.7	0.6
Yb	1.7	1.2	1.4	2.2	1.5
Lu	0.27	0.19	0.22	0.37	0.24
LaN/YbN	8.08	8.13	8.76	8.22	9.23
La/Yb	12.24	12.33	13.29	12.45	14.00
La/Sm	5.20	5.92	5.64	5.37	5.38
Hf/Yb	3.00	3.42	3.79	3.95	3.47

American Tickle Trace Elements (cont.)

Element	GT B10	SB 2	SB B3	SAB 3*	LSI 5
Ba	227	1243	352	320	444
Sr	488	114	305	459	227
Zr	148	210	100	49	180
Y	18	20	22	20	20
Be	<1	<1	<1	<1	<1
Cu	30	40	15	15	45
Ni	180	100	40	10	230
Pb	<50	<50	<50	<50	<50
V	68	62	44	14	62
Zn	85	100	100	75	90
Ag	<0.1	<0.1	<0.1	<0.1	0.1
Nb	<30	<30	<30	<30	<30
Au	6	7	6	10	5
As	3	3	4	2	7
Br	<1	<1	<1	<1	<1
Co	20	15	17	7	28
Cr	1400	160	110	48	580
Cs	<0.5	3.3	2	1.7	1.6
Hf	3.9	5.5	2.6	1.4	4.7
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	25	79	43	35	71
Sb	2.8	0.8	2	2.2	4.9
Sc	13	10	7.8	3.6	13
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	<1	<1
Th	3.9	7.6	5.3	2.9	5.1
U	<0.5	2.3	1.4	1	1.3
W	<3	<3	<3	<3	<3
La	13.5	28.1	19.9	12.7	19.7
Ce	33	67	49	34	45
Nd	13	31	20	18	20
Sm	2.8	4.8	4.5	3.5	3.5
Eu	0.8	1	1	0.9	0.9
Tb	0.5	0.6	0.6	0.7	0.7
Yb	1.2	1.7	1.7	1.4	1.6
Lu	0.21	0.28	0.25	0.19	0.25
LaN/YbN	7.42	10.91	7.73	5.98	8.12
La/Yb	11.25	16.53	11.71	9.07	12.31
La/Sm	4.82	5.85	4.42	3.63	5.63
Hf/Yb	3.25	3.24	1.53	1.00	2.94

American Tickle Trace Elements (cont.)

Element	SAB 10x	SB B2x
Ba	619	3602
Sr	115	363
Zr	182	103
Y	21	21
Be	n/a	n/a
Cu	21	9
Ni	76	36
Pb	13	<12
V	74	36
Zn	63	32
Ag	n/a	n/a
Nb	14	6
Au	n/a	n/a
As	n/a	n/a
Br	n/a	n/a
Co	46	20
Cr	117	80
Cs	n/a	n/a
Hf	4.338	2.792
Hg	n/a	n/a
Ir	n/a	n/a
Mo	n/a	n/a
Rb	72	25
Sb	n/a	n/a
Sc	8	10
Se	n/a	n/a
Ta	1.426	0.584
Th	10	3
U	4	<16
W	n/a	n/a
La	26.059	17.093
Ce	53.335	34.859
Nd	22.914	16.68
Sm	4.44	3.66
Eu	0.925	0.477
Tb	0.521	0.507
Yb	1.621	1.573
Lu	0.249	0.22
LaN/YbN	10.61	7.17
La/Yb	16.08	10.87
La/Sm	5.87	4.67
Hf/Yb	2.68	1.77

Mainland Major Elements

	ML 8	ML 11	ML 15	ML 23
Grainsize	vcrs	vcrs	f	med/crs
Structure	mass/lam	mass/lam	lam	mass
SiO_2	71.53	75.82	63.12	73.33
TiO_2	0.65	0.29	1.01	0.22
Al_2O_3	7.99	5.25	7.98	3.88
Fe_2O_3	4.95	3.40	4.32	1.92
MnO	0.18	0.14	0.36	0.32
MgO	3.73	3.58	3.52	1.16
CaO	8.21	9.52	16.27	17.40
Na_2O	1.22	0.90	1.41	0.72
K_2O	1.40	0.95	1.78	1.03
P_2O_5	0.16	0.15	0.23	0.02
LOI	8.24	8.03	12.68	12.35
Analytical total	98.38	98.90	99.12	97.80
al-alk	11.37	7.51	6.91	3.71
Nig Ti	2.13	1.00	2.38	0.67
Nig Fm	32.70	31.31	22.55	10.86
Nig K	0.43	0.41	0.45	0.48
Nig Mg	0.59	0.67	0.60	0.50
Nig Si	309.11	352.53	198.43	293.38
Fe_2O_3+MgO	8.67	6.98	7.83	3.07
Al_2O_3/SiO_2	0.11	0.07	0.13	0.05
K_2O/Na_2O	1.15	1.05	1.26	1.42
$Al_2O_3/(CaO+Na_2O)$	0.85	0.50	0.45	0.21

Mainland Major Elements (cont.)

	ML 26	TRC 3	TRC 5	TRC 7
Grainsize	crs/vcrs	f	f/m	f
Structure	massive	lam	lam	lam
SiO_2	82.58	59.99	72.65	69.96
TiO_2	0.23	0.69	0.47	0.78
Al_2O_3	3.25	9.16	8.73	10.19
Fe_2O_3	1.68	4.18	4.55	5.26
MnO	0.10	0.43	0.10	0.12
MgO	1.30	3.12	4.20	3.86
CaO	9.26	18.60	5.99	6.03
Na_2O	0.62	1.70	1.46	1.49
K_2O	0.95	1.99	1.73	2.18
P_2O_5	0.02	0.14	0.13	0.13
LOI	7.48	14.67	6.85	6.84
Analytical total	97.96	100.03	98.14	99.53
al-alk	4.51	7.12	11.88	13.72
Nig Ti	1.11	1.49	1.60	2.52
Nig Fm	16.94	18.91	36.37	33.88
Nig K	0.50	0.44	0.44	0.49
Nig Mg	0.59	0.57	0.64	0.59
Nig Si	525.87	172.24	328.30	302.34
Fe_2O_3+MgO	2.98	7.30	8.74	9.13
Al_2O_3/SiO_2	0.04	0.15	0.12	0.15
K_2O/Na_2O	1.54	1.17	1.19	1.46
$Al_2O_3/(CaO+Na_2O)$	0.33	0.45	1.17	1.36

Mainland Major Elements (cont.)

	TRC A1	TRC A5	TRC A7	TRC A10
Grainsize	crs	crs/vcrs	f/crs	f
Structure	mass	lam	lam/gr	con
SiO_2	76.01	78.74	73.31	69.03
TiO_2	0.44	0.25	0.45	0.72
Al_2O_3	7.09	5.14	8.07	10.13
Fe_2O_3	4.02	3.05	4.50	5.44
MnO	0.10	0.14	0.12	0.18
MgO	3.77	3.18	4.45	4.08
CaO	5.88	7.57	6.26	6.41
Na_2O	1.19	0.71	1.10	1.62
K_2O	1.43	1.09	1.65	2.17
P_2O_5	0.09	0.13	0.09	0.22
LOI	6.57	7.48	7.01	7.61
Analytical total	100.12	99.23	97.75	99.78
al-alk	10.69	8.87	11.95	12.54
Nig Ti	1.67	1.02	1.54	2.21
Nig Fm	36.54	32.46	38.30	34.42
Nig K	0.44	0.50	0.50	0.47
Nig Mg	0.64	0.66	0.66	0.59
Nig Si	384.78	424.95	333.01	286.80
Fe_2O_3+MgO	7.79	6.24	8.95	9.52
Al_2O_3/SiO_2	0.09	0.07	0.11	0.15
K_2O/Na_2O	1.21	1.54	1.50	1.34
$Al_2O_3/(CaO+Na_2O)$	1.00	0.62	1.10	1.26

Mainland Major Elements (cont.)

	TRC A13	TRC A16	TRC A20	TRC A25
Grainsize	f	f	f	crs/vcrs
Structure	lam	lam	mass	mass
SiO_2	66.17	69.75	73.89	72.61
TiO_2	0.75	0.78	0.64	0.34
Al_2O_3	10.90	10.56	8.90	5.47
Fe_2O_3	5.36	5.23	4.72	3.03
MnO	0.22	0.09	0.09	0.27
MgO	4.90	4.04	4.03	2.62
CaO	7.39	5.54	4.57	13.55
Na_2O	1.73	1.62	1.29	0.92
K_2O	2.38	2.25	1.79	1.18
P_2O_5	0.18	0.15	0.09	0.02
LOI	9.18	6.57	5.59	10.72
Analytical total	98.16	97.98	99.41	99.20
al-alk	11.93	13.84	13.99	6.43
Nig Ti	2.09	2.52	2.36	1.03
Nig Fm	35.16	34.71	38.52	21.41
Nig K	0.48	0.48	0.48	0.46
Nig Mg	0.63	0.60	0.62	0.61
Nig Si	244.58	300.38	362.41	294.51
Fe_2O_3+MgO	10.26	9.27	8.75	5.65
Al_2O_3/SiO_2	0.16	0.15	0.12	0.08
K_2O/Na_2O	1.38	1.39	1.39	1.28
$Al_2O_3/(CaO+Na_2O)$	1.19	1.48	1.52	0.38

Mainland Major Elements (cont.)

	TRC A28	LP B1	ML 4	ML B9
Grainsize	m/crs	med	f	med/crs
Structure	xbed	mass	con	mass
SiO_2	76.68	78.78	38.82	69.92
TiO_2	0.45	0.26	0.44	0.36
Al_2O_3	6.28	6.57	7.95	6.40
Fe_2O_3	3.34	3.04	4.30	3.48
MnO	0.17	0.11	0.72	0.23
MgO	2.84	2.54	3.44	3.38
CaO	7.68	6.02	41.46	13.50
Na_2O	1.10	1.11	0.82	1.07
K_2O	1.34	1.48	1.93	1.50
P_2O_5	0.11	0.09	0.18	0.09
LOI	7.19	6.85	26.69	11.82
Analytical total	99.88	98.88	98.81	99.97
al-alk	9.14	10.69	4.55	6.66
Nig Ti	1.75	1.13	0.57	1.02
Nig Fm	28.92	28.95	12.58	24.44
Nig K	0.44	0.47	0.61	0.48
Nig Mg	0.61	0.61	0.57	0.64
Nig Si	393.53	453.60	66.40	261.54
Fe_2O_3+MgO	6.18	5.58	7.74	6.86
Al_2O_3/SiO_2	0.08	0.08	0.20	0.09
K_2O/Na_2O	1.22	1.33	2.35	1.40
$Al_2O_3/(CaO+Na_2O)$	0.71	0.92	0.18	0.43

Mainland Formation Trace Elements

Element	ML 8	ML 11*	ML 15*	ML 23	ML 26
Ba	227	263	283	143	163
Sr	124	147	168	108	117
Zr	143	90	361	67	98
Y	18	16	30	16	12
Be	<1	<1	<1	<1	<1
Cu	30	25	30	15	15
Ni	110	170	110	40	90
Pb	<50	<50	<50	<50	<50
V	70	38	58	20	28
Zn	80	70	75	50	60
Ag	<0.1	<0.1	<0.1	<0.1	0.2
Nb	30	30	30	30	30
Au	<5	<5	<5	<5	115
As	5	10	13	4	6
Br	<1	2	2	2	2
Co	15	15	19	6	11
Cr	290	510	1030	230	740
Cs	1.3	1	1.3	1.3	<0.5
Hf	2.6	1.9	8.3	1.9	2.8
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	53	21	33	28	21
Sb	1.2	1.4	1.1	0.8	4
Sc	10	6	9.6	3.4	4.2
Se	<3	<3	<3	<3	<3
Ta	<1	<1	2	<1	<1
Th	4.2	2.9	6.4	2.6	3.1
U	1.9	1.3	1.9	1.4	1.1
W	<3	<3	<3	<3	<3
La	16	12.7	25.6	13	12.3
Ce	40	33	62	31	28
Nd	17	16	23	12	14
Sm	3.5	2.8	4.9	2.2	2.1
Eu	0.9	0.6	1.2	0.5	0.5
Tb	0.7	0.5	0.9	<0.5	<0.5
Yb	1.4	1.1	2.2	0.9	0.8
Lu	0.21	0.15	0.36	0.16	0.13
LaN/YbN	7.53	7.61	7.68	9.52	10.13
La/Yb	11.43	11.55	11.64	14.44	15.38
La/Sm	4.57	4.54	5.22	5.91	5.86
Hf/Yb	1.86	1.73	3.77	2.11	3.50

Mainland Formation Trace Elements (cont.)

Element	TRC 3	TRC 5	TRC 7#	TRC A1	TRC A5
Ba	320	720	550	290	269
Sr	224	135	144	124	146
Zr	301	160	610	144	78
Y	26	16	26	16	18
Be	<1	<1	<1	<1	<1
Cu	30	35	35	25	20
Ni	100	140	120	140	160
Pb	<50	<50	<50	<50	<50
V	54	54	66	52	42
Zn	85	90	120	80	90
Ag	<0.1	0.5	0.1	<0.1	<0.1
Nb	30	30	30	30	30
Au	6	32	<5	<5	7
As	5	4	6	5	10
Br	2	1	2	2	1
Co	13	15	18	13	21
Cr	350	260	630	430	470
Cs	1.3	1.3	1.9	1.5	<0.5
Hf	6.8	3.5	16	3.4	1.9
Hg	<1	<1	<1	<1	<1
Ir	9	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	45	58	65	<20	26
Sb	1.3	12	2.3	1.6	1.8
Sc	9.1	8.3	10	7.6	5.7
Se	<3	<3	<3	<3	<3
Ta	<1	1	<1	<1	<1
Th	6	5	11	4	2.9
U	1.6	1.6	2.9	1.7	1.4
W	<3	<3	<3	<3	<3
La	22.4	16.2	29.8	15.4	14.7
Ce	54	40	70	37	41
Nd	24	19	30	16	20
Sm	4.2	3.3	5.3	3.2	3.7
Eu	1.1	0.9	1.1	0.7	0.9
Tb	0.7	0.5	0.6	0.5	0.5
Yb	2	1.4	2.8	1.2	1
Lu	0.32	0.23	0.48	0.2	0.16
LaN/YbN	7.39	7.63	7.02	8.46	9.7
La/Yb	11.20	11.57	10.64	12.83	14.70
La/Sm	5.33	4.91	5.62	4.81	3.97
Hf/Yb	3.40	2.50	5.71	2.83	1.90

Mainland Formation Trace Elements (cont.)

Element	TRC A7	TRC A10*	TRC A13*	TRC A16*	TRC A20*
Ba	326	395	408	430	359
Sr	140	179	144	144	119
Zr	225	484	366	534	394
Y	18	26	26	26	18
Be	<1	<1	<1	<1	<1
Cu	30	40	40	35	30
Ni	140	130	110	130	150
Pb	<50	<50	<50	<50	<50
V	52	56	58	58	64
Zn	110	130	90	110	100
Ag	<0.1	0.2	0.6	<0.1	<0.1
Nb	30	30	30	30	30
Au	<5	<5	5	<5	38
As	6	6	5	6	5
Br	<1	<1	<1	<1	<1
Co	17	23	19	20	22
Cr	470	370	290	540	750
Cs	1.5	2.3	2.2	1.8	1.7
Hf	4.7	9.8	8.7	13	8.6
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	46	69	64	65	43
Sb	1.1	2.5	2.4	1.6	1.5
Sc	7.3	9.4	10	9	8.7
Se	<3	<3	<3	<3	4
Ta	<1	<1	<1	<1	<1
Th	5.6	7.8	8	9.3	7.6
U	2.3	2.9	2.3	2.4	2.8
W	<3	<3	<3	<3	<3
La	18.8	25.3	25	25.6	20.6
Ce	47	62	61	65	52
Nd	22	27	28	27	21
Sm	3.7	5.2	5	4.9	3.9
Eu	0.8	1.1	1.1	1.1	0.9
Tb	0.5	0.9	0.8	0.8	0.6
Yb	1.5	2.5	2.4	2.5	1.8
Lu	0.25	0.4	0.43	0.39	0.3
LaN/YbN	8.26	6.68	6.87	6.75	7.55
La/Yb	12.53	10.12	10.42	10.24	11.44
La/Sm	5.08	4.87	5.00	5.22	5.28
Hf/Yb	3.13	3.92	3.63	5.20	4.78

Mainland Formation Trace Elements (cont.)

Element	TRC A25	TRC A28#	LP B1x	ML 4#	ML B9#
Ba	237	328	361	3021	325
Sr	186	149	73	190	137
Zr	126	168	83	93	74
Y	18	18	14	29	16
Be	<1	<1	n/a	n/a	n/a
Cu	20	20	12	11	13
Ni	120	110	112	45	151
Pb	<50	<50	9	12	10
V	38	40	53	61	60
Zn	140	85	38	35	38
Ag	<0.1	<0.1	n/a	n/a	n/a
Nb	30	30	5	7	4
Au	7	7	n/a	n/a	n/a
As	6	5	n/a	n/a	n/a
Br	1	<1	n/a	n/a	n/a
Co	17	14	42	17	33
Cr	430	760	216	79	278
Cs	<0.5	1.1	n/a	n/a	n/a
Hf	2.8	3.7	2.222	2.518	1.881
Hg	<1	<1	n/a	n/a	n/a
Ir	<5	<5	n/a	n/a	n/a
Mo	<5	<5	n/a	n/a	n/a
Rb	-20	31	37	45	35
Sb	1.8	1	n/a	n/a	n/a
Sc	5.9	6.4	10	7	13
Se	<3	<3	n/a	n/a	n/a
Ta	<1	<1	0.751	0.559	0.575
Th	3.3	4	4	7	7
U	1.5	1.3	<16	<16	<16
W	<3	<3	n/a	n/a	n/a
La	15.5	16.2	12.813	25.681	15.83
Ce	39	43	26.169	51.375	30.974
Nd	17	17	11.544	23.165	13.996
Sm	3.2	3.6	2.3055	4.264	2.633
Eu	0.7	0.8	0.493	0.655	0.664
Tb	0.6	0.5	0.314	0.629	0.360
Yb	1.3	1.4	0.928	1.575	1.113
Lu	0.19	0.18	0.134	0.236	0.136
LaN/YbN	7.87	7.62	9.11	10.76	9.38
La/Yb	11.92	11.57	13.81	16.31	14.22
La/Sm	4.84	4.50	5.56	5.55	6.01
Hf/Yb	2.15	2.64	2.39	1.60	1.69

Mainland Formation Trace Elements (cont.)

Element	ML 8	ML 11*	ML 15*	ML 23	ML 26
Ba	227	263	283	143	163
Sr	124	147	168	108	117
Zr	143	90	361	67	98
Y	18	16	30	16	12
Be	<1	<1	<1	<1	<1
Cu	30	25	30	15	15
Ni	110	170	110	40	90
Pb	<50	<50	<50	<50	<50
V	70	38	58	20	28
Zn	80	70	75	50	60
Ag	<0.1	<0.1	<0.1	<0.1	0.2
Nb	30	30	30	30	30
Au	<5	<5	<5	<5	115
As	5	10	13	4	6
Br	<1	2	2	2	2
Co	15	15	19	6	11
Cr	290	510	1030	230	740
Cs	1.3	1	1.3	1.3	<0.5
Hf	2.6	1.9	8.3	1.9	2.8
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	53	21	33	28	21
Sb	1.2	1.4	1.1	0.8	4
Sc	10	6	9.6	3.4	4.2
Se	<3	<3	<3	<3	<3
Ta	<1	<1	2	<1	<1
Th	4.2	2.9	6.4	2.6	3.1
U	1.9	1.3	1.9	1.4	1.1
W	<3	<3	<3	<3	<3
La	16	12.7	25.6	13	12.3
Ce	40	33	62	31	28
Nd	17	16	23	12	14
Sm	3.5	2.8	4.9	2.2	2.1
Eu	0.9	0.6	1.2	0.5	0.5
Tb	0.7	0.5	0.9	<0.5	<0.5
Yb	1.4	1.1	2.2	0.9	0.8
Lu	0.21	0.15	0.36	0.16	0.13
LaN/YbN	7.53	7.61	7.68	9.52	10.13
La/Yb	11.43	11.55	11.64	14.44	15.38
La/Sm	4.57	4.54	5.22	5.91	5.86
Hf/Yb	1.86	1.73	3.77	2.11	3.50

Mainland Formation Trace Elements (cont.)

Element	TRC 3	TRC 5	TRC 7#	TRC A1	TRC A5
Ba	320	720	550	290	269
Sr	224	135	144	124	146
Zr	301	160	610	144	78
Y	26	16	26	16	18
Be	<1	<1	<1	<1	<1
Cu	30	35	35	25	20
Ni	100	140	120	140	160
Pb	<50	<50	<50	<50	<50
V	54	54	66	52	42
Zn	85	90	120	80	90
Ag	<0.1	0.5	0.1	<0.1	<0.1
Nb	30	30	30	30	30
Au	6	32	<5	<5	7
As	5	4	6	5	10
Br	2	1	2	2	1
Co	13	15	18	13	21
Cr	350	260	630	430	470
Cs	1.3	1.3	1.9	1.5	<0.5
Hf	6.8	3.5	16	3.4	1.9
Hg	<1	<1	<1	<1	<1
Ir	9	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	45	58	65	<20	26
Sb	1.3	12	2.3	1.6	1.8
Sc	9.1	8.3	10	7.6	5.7
Se	<3	<3	<3	<3	<3
Ta	<1	1	<1	<1	<1
Th	6	5	11	4	2.9
U	1.6	1.6	2.9	1.7	1.4
W	<3	<3	<3	<3	<3
La	22.4	16.2	29.8	15.4	14.7
Ce	54	40	70	37	41
Nd	24	19	30	16	20
Sm	4.2	3.3	5.3	3.2	3.7
Eu	1.1	0.9	1.1	0.7	0.9
Tb	0.7	0.5	0.6	0.5	0.5
Yb	2	1.4	2.8	1.2	1
Lu	0.32	0.23	0.48	0.2	0.16
LaN/YbN	7.39	7.63	7.02	8.46	9.7
La/Yb	11.20	11.57	10.64	12.83	14.70
La/Sm	5.33	4.91	5.62	4.81	3.97
Hf/Yb	3.40	2.50	5.71	2.83	1.90

Mainland Formation Trace Elements (cont.)

Element	TRC A7	TRC A10*	TRC A13*	TRC A16*	TRC A20*
Ba	326	395	408	430	359
Sr	140	179	144	144	119
Zr	225	484	366	534	394
Y	18	26	26	26	18
Be	<1	<1	<1	<1	<1
Cu	30	40	40	35	30
Ni	140	130	110	130	150
Pb	<50	<50	<50	<50	<50
V	52	56	58	58	64
Zn	110	130	90	110	100
Ag	<0.1	0.2	0.6	<0.1	<0.1
Nb	30	30	30	30	30
Au	<5	<5	5	<5	38
As	6	6	5	6	5
Br	<1	<1	<1	<1	<1
Co	17	23	19	20	22
Cr	470	370	290	540	750
Cs	1.5	2.3	2.2	1.8	1.7
Hf	4.7	9.8	8.7	13	8.6
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	46	69	64	65	43
Sb	1.1	2.5	2.4	1.6	1.5
Sc	7.3	9.4	10	9	8.7
Se	<3	<3	<3	<3	4
Ta	<1	<1	<1	<1	<1
Th	5.6	7.8	8	9.3	7.6
U	2.3	2.9	2.3	2.4	2.8
W	<3	<3	<3	<3	<3
La	18.8	25.3	25	25.6	20.6
Ce	47	62	61	65	52
Nd	22	27	28	27	21
Sm	3.7	5.2	5	4.9	3.9
Eu	0.8	1.1	1.1	1.1	0.9
Tb	0.5	0.9	0.8	0.8	0.6
Yb	1.5	2.5	2.4	2.5	1.8
Lu	0.25	0.4	0.43	0.39	0.3
LaN/YbN	8.26	6.68	6.87	6.75	7.55
La/Yb	12.53	10.12	10.42	10.24	11.44
La/Sm	5.08	4.87	5.00	5.22	5.28
Hf/Yb	3.13	3.92	3.63	5.20	4.78

Mainland Formation Trace Elements (cont.)

Element	TRC A25	TRC A28#	LP B1x	ML 4#	ML B9#
Ba	237	328	361	3021	325
Sr	186	149	73	190	137
Zr	126	168	83	93	74
Y	18	18	14	29	16
Be	<1	<1	n/a	n/a	n/a
Cu	20	20	12	11	13
Ni	120	110	112	45	151
Pb	<50	<50	9	12	10
V	38	40	53	61	60
Zn	140	85	38	35	38
Ag	<0.1	<0.1	n/a	n/a	n/a
Nb	30	30	5	7	4
Au	7	7	n/a	n/a	n/a
As	6	5	n/a	n/a	n/a
Br	1	<1	n/a	n/a	n/a
Co	17	14	42	17	33
Cr	430	760	216	79	278
Cs	<0.5	1.1	n/a	n/a	n/a
Hf	2.8	3.7	2.222	2.518	1.881
Hg	<1	<1	n/a	n/a	n/a
Ir	<5	<5	n/a	n/a	n/a
Mo	<5	<5	n/a	n/a	n/a
Rb	-20	31	37	45	35
Sb	1.8	1	n/a	n/a	n/a
Sc	5.9	6.4	10	7	13
Se	<3	<3	n/a	n/a	n/a
Ta	<1	<1	0.751	0.559	0.575
Th	3.3	4	4	7	7
U	1.5	1.3	<16	<16	<16
W	<3	<3	n/a	n/a	n/a
La	15.5	16.2	12.813	25.681	15.83
Ce	39	43	26.169	51.375	30.974
Nd	17	17	11.544	23.165	13.996
Sm	3.2	3.6	2.3055	4.264	2.633
Eu	0.7	0.8	0.493	0.655	0.664
Tb	0.6	0.5	0.314	0.629	0.360
Yb	1.3	1.4	0.928	1.575	1.113
Lu	0.19	0.18	0.134	0.236	0.136
LaN/YbN	7.87	7.62	9.11	10.76	9.38
La/Yb	11.92	11.57	13.81	16.31	14.22
La/Sm	4.84	4.50	5.56	5.55	6.01
Hf/Yb	2.15	2.64	2.39	1.60	1.69

Lower Head Formation Major Elements

Element	BBN 1	EI 2	EI 4	EI 6
Grainsize	f	f/vcrs	med	med
Structure	rip	lam/gr	mass	mass
SiO_2	73.19	81.13	76.40	76.75
TiO_2	0.76	0.46	0.47	0.56
Al_2O_3	10.56	7.59	7.53	9.73
Fe_2O_3	5.76	3.88	3.83	4.25
MnO	0.19	0.11	0.10	0.05
MgO	3.51	2.91	2.39	3.64
CaO	2.42	1.16	6.34	1.29
Na_2O	2.33	1.11	1.99	2.14
K_2O	1.18	1.62	0.94	1.52
P_2O_5	0.08	0.02	0.02	0.06
LOI	4.40	3.43	6.43	3.17
TOTAL	98.95	99.50	98.32	97.62
a'-alk	16.57	17.16	10.13	15.60
Nig Ti	2.95	2.51	1.87	2.45
Nig Fm	27.82	32.36	19.37	31.77
Nig K	0.25	0.49	0.24	0.32
Nig Mg	0.54	0.59	0.55	0.63
Nig Si	377.44	591.08	405.34	445.38
Fe_2O_3+MgO	9.27	6.80	6.22	7.89
Al_2O_3/SiO_2	0.14	0.09	0.10	0.13
K_2O/Na_2O	0.51	1.46	0.47	0.71
$Al_2O_3/(CaO+Na_2O)$	2.22	3.34	0.90	2.84

Lower Head Formation Major Elements (cont.)

Element	MAP B1	MAP B3	MAP B10	MAP B7
Grainsize	med/crs	f	med	med
Structure	mass	mass	x-bed	mass
SiO_2	79.89	70.85	74.73	76.95
TiO_2	0.49	0.85	1.03	0.63
Al_2O_3	7.67	11.43	7.32	8.43
Fe_2O_3	3.99	5.57	5.04	4.67
MnO	0.14	0.54	0.21	0.06
MgO	3.43	4.32	2.53	3.36
CaO	1.92	2.09	6.62	2.64
Na_2O	1.84	1.77	1.68	1.53
K_2O	0.61	2.46	0.83	1.67
P_2O_5	0.02	0.13	0.02	0.08
LOI	3.48	4.87	6.09	4.35
TOTAL	97.82	98.28	97.68	99.22
al-alk	15.11	16.26	11.11	14.14
Nig Ti	2.37	2.99	3.97	2.77
Nig Fm	33.79	32.47	20.34	29.54
Nig K	0.18	0.48	0.25	0.42
Nig Mg	0.62	0.58	0.49	0.59
Nig Si	515.92	333.43	385.17	448.64
Fe_2O_3+MgO	7.42	9.89	7.57	8.03
Al_2O_3/SiO_2	0.10	0.16	0.10	0.11
K_2O/Na_2O	0.33	1.39	0.49	1.09
$Al_2O_3/(CaO+Na_2O)$	2.04	2.97	0.88	2.03

Lower Head Formation Major Elements (cont.)

Element	LHN B4	LHN B6	LHS B2	LHS B5
Grainsize	crs	crs	f	med/crs
Structure	mass	mass	lam	mass
SiO_2	65.37	67.65	53.89	69.84
TiO_2	0.57	0.63	0.73	0.66
Al_2O_3	9.14	9.39	11.62	10.30
Fe_2O_3	4.49	3.87	6.35	5.33
MnO	0.18	0.16	0.13	0.07
MgO	3.23	2.75	4.94	4.43
CaO	13.31	11.54	18.41	5.44
Na_2O	1.84	1.84	1.49	1.78
K_2O	1.84	2.15	2.41	2.11
P_2O_5	0.02	0.02	0.02	0.04
LOI	11.18	9.72	15.45	6.47
TOTAL	99.06	99.77	99.15	98.27
al-alk	8.29	8.87	9.79	12.71
Nig Ti	1.46	1.78	1.39	2.11
Nig Fm	16.97	15.83	18.97	28.20
Nig K	0.40	0.43	0.52	0.44
Nig Mg	0.58	0.57	0.60	0.62
Nig Si	223.33	252.97	136.67	295.54
Fe_2O_3+MgO	7.72	6.62	11.30	9.76
Al_2O_3/SiO_2	0.14	0.14	0.22	0.15
K_2O/Na_2O	1.00	1.17	1.62	1.19
$Al_2O_3/(CaO+Na_2O)$	0.60	0.70	0.58	1.43

Lower Head Formation Major Elements (cont.)

Element	LHS B8	LHS B10	MPN 8	MPS 11
Grainsize	crs	med/crs	crs	vcr-
Structure	mass	mass	mass	mass
SiO_2	69.71	72.12	66.21	78.76
TiO_2	0.55	0.82	0.52	0.32
Al_2O_3	9.20	10.27	8.06	7.25
Fe_2O_3	4.46	5.85	3.38	3.48
MnO	0.10	0.04	0.37	0.07
MgO	3.68	4.80	2.52	2.92
CaO	8.42	1.84	15.43	4.02
Na_2O	1.93	2.15	1.61	1.49
K_2O	1.93	2.09	1.88	1.67
P_2O_5	0.02	0.02	0.02	0.02
LOI	8.05	3.73	12.41	4.98
TOTAL	99.12	97.65	99.45	100.48
al-alk	9.35	12.64	6.77	10.50
Nig Ti	1.66	2.96	1.32	1.45
Nig Fm	22.48	34.54	13.87	26.26
Nig K	0.40	0.39	0.44	0.43
Nig Mg	0.61	0.62	0.57	0.62
Nig Si	281.12	346.13	225.31	468.70
Fe_2O_3+MgO	8.15	10.65	5.91	6.40
Al_2O_3/SiO_2	0.13	0.14	0.12	0.09
K_2O/Na_2O	1.00	0.97	1.17	1.13
$Al_2O_3/(CaO+Na_2O)$	0.89	2.57	0.47	1.32

Lower Head Formation Major Elements (cont.)

Element	MPS 13	MPS 23	PORT 1	PORT
Grainsize	crs	med	f	f
Structure	mass	mass	rip/lam	lam
SiO_2	77.26	77.20	70.38	78.42
TiO_2	0.49	0.49	0.55	0.31
Al_2O_3	7.98	7.84	8.69	5.82
Fe_2O_3	4.13	3.97	3.34	2.04
MnO	0.05	0.05	0.11	0.09
MgO	4.13	3.52	2.61	1.57
CaO	2.74	3.78	10.31	8.85
Na_2O	1.64	1.55	1.96	1.64
K_2O	1.56	1.56	2.03	1.20
P_2O_5	0.02	0.02	0.02	0.07
LOI	4.07	4.75	9.12	7.43
TOTAL	99.14	99.37	100.69	99.14
al-alk	11.79	11.79	7.80	5.86
Nig Ti	2.07	2.04	1.67	1.24
Nig Fm	34.50	29.46	16.18	13.09
Nig K	0.38	0.40	0.40	0.33
Nig Mg	0.66	0.63	0.60	0.59
Nig Si	429.77	429.70	286.10	425.13
Fe_2O_3+MgO	8.26	7.49	5.95	3.61
Al_2O_3/SiO_2	0.10	0.10	0.12	0.07
K_2O/Na_2O	0.95	1.01	1.03	0.73
$Al_2O_3/(CaO+Na_2O)$	1.82	1.47	0.71	0.56

Lower Head Formation Major Elements (cont.)

Element	PORT B2	WBN 6	WBN A3	WBN A15
Grainsize	crs	crs/vcrs	crs/vcrs	crs
Structure	mass	mass	mass	mass
SiO_2	75.31	76.63	75.51	79.71
TiO_2	0.34	0.49	0.49	0.37
Al_2O_3	6.78	8.83	9.09	7.02
Fe_2O_3	2.46	4.07	4.50	3.48
MnO	0.11	0.07	0.07	0.05
MgO	1.90	3.55	3.39	2.85
CaO	9.72	2.85	3.42	3.79
Na_2O	1.84	1.66	1.63	1.37
K_2O	1.52	1.83	1.86	1.32
P_2O_5	0.02	0.02	0.02	0.02
LOI	8.53	4.66	4.79	4.65
TOTAL	99.18	99.82	100.17	100.02
al-alk	5.90	13.54	13.89	12.30
Nig Ti	1.22	2.07	1.99	1.73
Nig Fm	13.90	29.90	27.53	26.87
Nig K	0.35	0.42	0.43	0.39
Nig Mg	0.59	0.63	0.59	0.61
Nig Si	358.40	427.78	405.81	498.75
Fe_2O_3÷MgO	4.35	7.62	7.90	6.33
Al_2O_3/SiO_2	0.09	0.12	0.12	0.09
K_2O/Na_2O	0.83	1.10	1.14	0.96
$Al_2O_3/(CaO÷Na_2O)$	0.59	1.96	1.80	1.36

Lower Head Formation Major Elements (cont.)

Element Grainsize Structure	WBS 9 med/vcrs mass	WBS B1 med/crs mass	WBS B2 crs/vcrs mass	LHS B12 vcrs mass
SiO_2	78.12	72.66	75.76	65.34
TiO_2	0.41	0.48	0.53	0.51
Al_2O_3	7.57	8.01	9.56	8.27
Fe_2O_3	2.92	3.52	3.84	3.37
MnO	0.08	0.18	0.13	0.09
MgO	2.79	2.43	4.06	2.27
CaO	4.92	9.38	2.52	16.48
Na_2O	1.62	1.64	1.64	1.82
K_2O	1.54	1.62	1.94	1.79
P_2O_5	0.02	0.09	0.02	0.06
LOI	5.19	8.31	4.38	12.54
TOTAL	97.51	100.59	99.08	99.17
al-alk	10.82	9.32	14.94	6.50
Nig Ti	1.76	1.59	2.11	1.27
Nig Fm	24.01	16.78	32.81	11.49
Nig K	0.38	0.40	0.44	0.39
Nig Mg	0.65	0.56	0.67	0.56
Nig Si	443.56	323.09	403.62	216.52
Fe_2O_3+MgO	5.72	5.95	7.90	5.64
Al_2O_3/SiO_2	0.10	0.11	0.13	0.13
K_2O/Na_2O	0.95	0.99	1.18	0.98
$Al_2O_3/(CaO+Na_2O)$	1.16	0.73	2.30	0.45

Lower Head Formation Major Elements (cont.)

Element	BP 3	BP 7	BP 10	RPA 2
Grainsize	crs	crs/vcrs	med/vcrs	f
Structure	mass	mass	mass	mass
SiO_2	72.24	75.15	62.06	71.21
TiO_2	0.71	0.59	0.61	0.63
Al_2O_3	10.14	9.03	8.62	11.22
Fe_2O_3	5.20	4.63	4.02	5.38
MnO	0.08	0.06	0.74	0.08
MgO	3.95	4.36	3.33	4.21
CaO	3.95	2.82	17.39	3.14
Na_2O	1.85	1.61	2.03	1.75
K_2O	1.82	1.71	1.18	2.31
P_2O_5	0.06	0.02	0.02	0.06
LOI	5.60	4.49	14.41	5.01
TOTAL	97.96	98.01	99.25	100.90
al-alk	14.32	13.82	7.05	15.97
Nig Ti	2.55	2.29	1.37	2.19
Nig Fm	28.26	33.97	16.70	29.51
Nig K	0.39	0.41	0.28	0.47
Nig Mg	0.60	0.65	0.58	0.60
Nig Si	342.78	389.33	185.06	330.84
Fe_2O_3-MgO	9.15	8.99	7.35	9.59
Al_2O-3/SiO_2	0.14	0.12	0.14	0.16
K_2O/Na_2O	0.98	1.06	0.58	1.32
$Al_2O_3/(CaO+Na_2O)$	1.75	2.04	0.44	2.29

Lower Head Formation Major Elements (cont.)

Element	RPA 11	RPA 14
Grainsize	med/crs	crs/vcrs
Structure	mass	mass
SiO_2	78.10	72.10
TiO_2	0.46	0.51
Al_2O_3	8.08	10.37
Fe_2O_3	4.40	5.08
MnO	0.14	0.10
MgO	4.00	3.48
CaO	2.23	4.51
Na_2O	1.16	1.61
K_2O	1.42	2.16
P_2O_5	0.02	0.07
LOI	4.18	6.53
TOTAL	100.18	99.67
al-alk	16.19	15.06
Nig Ti	2.04	1.83
Nig Fm	35.94	25.03
Nig K	0.45	0.47
Nig Mg	0.63	0.57
Nig Si	461.97	342.26
F_2O_3+MgO	8.40	8.57
Al_2O_3/SiO_2	0.10	0.14
K_2O/Na_2O	1.23	1.34
$Al_2O_3/(CaO+Na_2O)$	2.39	1.69

Lower Head Formation Trace Elements

Element	BBN 1	EI 2	EI 4*	EI 6	MAP B1*
Ba	558	776	1116	262	223
Sr	158	110	246	85	97
Zr	385	189	231	226	261
Y	20	14	16	14	14
Be	<1	<1	<1	<1	<1
Cu	45	90	15	25	25
Ni	120	40	80	120	120
Pb	50	50	50	50	50
V	56	64	44	52	48
Zn	95	90	70	80	70
Ag	0.1	1	0.9	0.4	0.1
Nb	30	30	30	30	30
Au	8	37	19	10	<5
As	9	<2	5	5	7
Br	<1	<1	1	<1	1
Co	15	19	9	13	13
Cr	320	220	213	210	383
Cs	<0.5	2.7	<0.5	<0.5	<0.5
Hf	8.6	4.2	5.7	5.9	6.6
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	35	45	<20	59	23
Sb	3.1	13	8.1	4.4	4.7
Sc	8	6.5	6.2	7.4	7.1
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	1	<1
Th	7.8	5.5	5.3	5.8	6.7
U	1.7	1.8	1.5	2.1	1.5
W	<3	<3	<3	<3	<3
La	22.3	17.1	15.7	17.9	19.4
Ce	53	39	37	40	45
Nd	22	12	16	15	21
Sm	4.3	2.8	2.9	3	3.2
Eu	0.9	0.6	0.7	0.7	0.8
Tb	0.5	0.5	0.5	0.5	0.5
Yb	2.1	1.2	1.3	1.4	1.7
Lu	0.29	0.23	0.21	0.21	0.26
LaN/YbN	7.00	9.40	7.97	8.43	7.53
La/Yb	10.62	14.25	12.08	12.79	11.41
La/Sm	5.19	6.12	5.41	5.97	6.06
Hf/Yb	4.10	3.50	4.38	4.21	3.88

Lower Head Formation Trace Elements (cont.)

SAMPLE	MAP B3*	MAP B10	MAP B7x	LHN B4	LHN B6
Ba	405	240	432	655	390
Sr	136	235	148	113	108
Zr	322	1293	297	191	267
Y	22	34	16	16	20
Be	<1	<1	n/a	<1	<1
Cu	40	15	16	20	25
Ni	70	100	121	120	110
Pb	50	50	14	50	50
V	88	64	77	54	52
Zn	85	75	47	70	70
Ag	<0.1	<0.1	n/a	0.1	<0.1
Nb	30	30	9	30	30
Au	<5	<5	n/a	6	6
As	<2	6	n/a	2	6
Br	<1	<1	n/a	1	1
Co	37	15	43	14	14
Cr	273	1100	406	310	320
Cs	4.1	<0.5	n/a	1.5	2.8
Hf	8.3	28	8.456	4.7	6.2
Hg	<1	<1	n/a	<1	<1
Ir	<5	<5	n/a	<5	<5
Mo	<5	<5	n/a	<5	<5
Rb	110	<20	43	66	58
Sb	1.8	1.6	n/a	1.5	1.1
Sc	10	8.1	5	9.5	9.3
Se	<3	9	n/a	<3	<3
Ta	<1	<1	1.286	<1	<1
Th	8.5	21	10	4.8	6.1
U	2.3	3.5	<1	1.4	1.6
W	<3	<3	n/a	<3	<3
La	23.1	45.7	21.925	17.5	20.1
Ce	55	103	45.956	41	49
Nd	22	40	19.4	15	21
Sm	4	6.5	3.577	2.9	3.6
Eu	0.9	1.3	0.736	0.7	0.9
Tb	0.6	0.7	0.444	0.5	0.6
Yb	2	3.1	1.703	1.4	1.7
Lu	0.31	0.52	0.256	0.21	0.26
LaN/YbN	7.62	9.72	8.49	8.24	7.80
La/Yb	11.55	14.74	12.87	12.50	11.82
La/Sm	5.78	7.03	3.06	6.03	5.58
Hf/Yb	4.15	9.03	4.96	3.36	3.64

Lower Head Formation Trace Elements (cont.)

SAMPLE	LHS B2	LHS B5	LHS B8	LHS B10	MPN 8
Ba	246	563	555	804	322
Sr	204	102	101	100	122
Zr	174	209	152	443	226
Y	26	16	14	18	18
Be	<1	<1	<1	<1	<1
Cu	35	25	25	35	25
Ni	110	140	120	150	90
Pb	50	50	50	50	50
V	64	64	56	82	44
Zn	80	80	70	75	60
Ag	<0.1	<0.1	0.1	<0.1	0.1
Nb	30	30	30	30	30
Au	<5	<5	10	6	<5
As	9	4	2	2	3
Br	<1	<1	<1	<1	1
Co	20	18	15	19	11
Cr	160	330	210	650	270
Cs	2.3	2.2	<0.5	<0.5	1
Hf	4.2	5.9	3.8	9.4	5.2
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	48	77	50	65	63
Sb	0.9	0.7	0.7	0.7	2.5
Sc	10	11	9	12	7.3
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	<1	<1
Th	6.4	6.3	4.7	7.3	5.5
U	2	1.6	1.2	1.7	1.9
W	<3	<3	<3	<3	<3
La	26.3	18.3	15.7	20.5	17.4
Ce	63	45	37	52	42
Nd	26	18	17	21	14
Sm	4.9	3.3	2.9	3.6	3.1
Eu	1.1	0.8	0.7	0.9	0.8
Tb	1	0.6	0.6	0.5	<0.5
Yb	2.1	1.5	1.4	1.9	1.6
Lu	0.34	0.26	0.23	0.32	0.25
LaN/YbN	8.26	8.04	7.39	7.12	7.18
La/Yb	12.52	12.20	11.21	10.79	10.87
La/Sm	5.36	5.55	5.41	5.69	5.61
Hf/Yb	2.00	3.93	2.71	4.95	3.25

Lower Head Formation Trace Elements (cont.)

SAMPLE	MPS 11	MPS 13	MPS 23	PORT 1	PORT 2
Ba	475	351	353	479	263
Sr	75	73	79	173	164
Zr	105	205	194	296	165
Y	12	12	14	18	10
Be	<1	<1	<1	<1	<1
Cu	20	30	25	20	15
Ni	100	130	120	60	50
Pb	50	50	50	50	50
V	42	56	56	34	24
Zn	75	75	95	95	70
Ag	0.1	<0.1	0.3	0.2	0.3
Nb	30	30	30	30	30
Au	<5	8	13	8	9
As	4	2	3	<2	<2
Br	2	2	2	<1	<1
Co	11	15	14	9	7
Cr	170	480	570	380	330
Cs	1	2	<0.5	1.5	<0.5
Hf	3.1	5.9	6.1	7.3	3.6
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	36	42	53	57	28
Sb	2.4	1.1	4.1	4.3	6.4
Sc	6.5	8.6	8.7	5.7	3.7
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	<1	<1
Th	3.5	5.6	5.4	5.8	3.5
U	1.1	1.7	1.7	1.6	0.6
W	<3	<3	<3	<3	<3
La	12.1	15.9	15.7	16.6	10.7
Ce	30	38	38	43	26
Nd	10	16	19	19	13
Sm	2.3	2.8	3	3	1.8
Eu	0.6	0.7	0.7	0.8	0.5
Tb	0.5	0.5	0.7	0.6	0.5
Yb	1.1	1.3	1.5	1.6	0.8
Lu	0.15	0.23	0.25	0.27	0.15
LaN/YbN	7.25	8.07	6.90	6.84	8.84
La/Yb	11.00	12.23	10.47	10.37	13.38
La/Sm	5.26	5.68	5.23	5.53	5.94
Hf/Yb	2.81	4.54	4.07	4.56	4.50

Lower Head Formation Trace Elements (cont.)

SAMPLE	PORT B2	WBN 6	WBN A3	WBN A15*	WBS 9
Ba	369	449	319	239	666
Sr	146	91	99	85	103
Zr	156	190	199	161	191
Y	10	12	14	12	14
Be	<1	<1	<1	<1	<1
Cu	20	25	25	20	5
Ni	30	120	110	90	80
Pb	50	50	50	50	50
V	28	50	58	44	44
Zn	75	70	120	60	60
Ag	<0.1	0.2	<0.1	<0.1	<0.1
Nb	30	30	30	30	30
Au	<5	<5	5	<5	<5
As	<2	3	3	<2	<2
Br	1	<1	<1	<1	<1
Co	7	13	13	11	9
Cr	240	270	300	263	290
Cs	<0.5	1.5	1.2	<0.5	1.5
Hf	3.4	4.5	4.6	3.6	4.6
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	48	62	59	31	39
Sb	0.9	0.7	0.6	1.3	<0.2
Sc	4.5	8.3	9.1	6.9	7.2
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	<1	<1
Th	3.4	5.1	5.1	3.6	4.3
U	1.2	1.2	1.3	1.1	1.2
W	<3	<3	<3	<3	<3
La	11.4	14	14.6	11.6	12.9
Ce	27	35	35	28	31
Nd	11	15	15	11	14
Sm	2	2.6	2.6	2.2	2.4
Eu	0.5	0.6	0.6	0.6	0.7
Tb	0.5	0.5	<0.5	<0.5	<0.5
Yb	0.9	1.3	1.3	1	1.1
Lu	0.15	0.19	0.2	0.15	0.18
LaN/YbN	8.35	7.10	7.41	7.66	7.73
La/Yb	12.67	10.77	11.23	11.60	11.73
La/Sm	5.70	5.38	5.62	5.27	5.38
Hf/Yb	3.78	3.46	3.54	3.60	4.18

Lower Head Formation Trace Elements (cont.)

SAMPLE	WBS B1	WBS B2*	LHS B12x	BP 3	BP 7
Ba	281	350	289	514	318
Sr	133	94	120	109	88
Zr	254	205	244	354	267
Y	18	14	15	22	18
Be	<1	<1	n/a	<1	<1
Cu	20	30	12	25	25
Ni	60	100	97	120	120
Pb	50	50	14	50	50
V	48	54	81	60	60
Zn	55	75	34	80	70
Ag	<0.1	<0.1	n/a	<0.1	<0.1
Nb	30	30	9	30	30
Au	<5	<5	n/a	<5	10
As	2	4	n/a	3	3
Br	<1	<1	n/a	1	<1
Co	11	25	33	13	15
Cr	340	243	411	400	410
Cs	1.2	2.1	n/a	1.8	<0.5
Hf	5.9	4.1	7.611	8.5	6.7
Hg	<1	<1	n/a	<1	<1
Ir	<5	<5	n/a	<5	<5
Mo	<5	<5	n/a	<5	<5
Rb	50	70	44	48	50
Sb	0.6	0.8	n/a	1.3	1.1
Sc	8.1	9.1	16	9.5	8.6
Se	<3	<3	n/a	<3	<3
Ta	<1	<1	0.865	<1	<1
Th	4.6	4.8	7	7.9	7.2
U	1.5	1.4	<4	1.8	1.6
W	<3	<3	n/a	<3	<3
La	16.3	15.3	19.798	22.6	19.4
Ce	41	37	39.229	53	46
Nd	18	16	16.361	22	18
Sm	3.1	2.7	3.107	3.9	3.4
Eu	0.8	0.6	0.573	0.9	0.7
Tb	<0.5	<0.5	0.398	0.6	0.6
Yb	1.6	1.3	1.498	1.9	1.4
Lu	0.23	0.22	0.231	0.29	0.28
LaN/YbN	6.72	7.77	8.72	7.85	9.13
La/Yb	10.19	11.77	13.21	11.89	13.86
La/Sm	5.26	5.67	3.19	5.79	5.71
Hf/Yb	3.67	3.15	5.08	4.47	4.79

Lower Head Formation Trace Elements (cont.)

SAMPLE	BP 10	RPA 2*	RPA 11*	RPA 14x
Ba	615	446	316	383
Sr	109	115	82	123
Zr	313	198	186	141
Y	24	20	16	20
Be	<1	<1	<1	n/a
Cu	20	25	25	16
Ni	70	160	150	130
Pb	50	50	50	13
V	46	56	46	67
Zn	80	90	85	54
Ag	<0.1	<0.1	<0.1	n/a
Nb	30	30	30	10
Au	<5	<5	<5	n/a
As	3	3	5	n/a
Br	<1	2	<1	n/a
Co	11	13	12	26
Cr	320	153	383	156
Cs	<0.5	1.2	<0.5	n/a
Hf	6.6	4.5	4	3.418
Hg	<1	<1	<1	n/a
Ir	<5	<5	10	n/a
Mo	<5	<5	<5	n/a
Rb	2	84	42	59
Sb	2	1	0.6	n/a
Sc	8.3	8.7	6.4	15
Se	<3	<3	<3	n/a
Ta	<1	<1	<1	0.924
Th	6.2	6.1	5.5	6
U	1.6	2.3	1.9	1
W	<3	<3	<3	n/a
La	23.8	20	16.6	20.267
Ce	53	48	40	41.609
Nd	19	22	15	18.661
Sm	3.8	3.8	3.1	3.733
Eu	0.9	0.9	0.6	0.805
Tb	0.5	0.7	0.6	0.524
Yb	1.8	1.7	1.4	1.449
Lu	0.28	0.27	0.19	0.217
LaN/YbN	8.72	7.76	7.81	9.23
La/Yb	13.22	11.76	11.86	13.99
La/Sm	6.26	5.26	5.35	2.71
Hf/Yb	3.67	2.65	2.86	2.36

A 5.7

Cambrian Sandstones Major Elements

SAMPLE	BMD 2	W1 B3	WF-76-85	BMD 8
grainsize	crs	crs	crs	crs
structure	mass	mass	mass	mass
SiO2	81.32	78.64	87.35	76.30
TiO2	0.52	0.59	0.42	0.66
Al2O3	8.19	10.87	5.76	11.89
Fe2O3	2.68	3.63	1.99	4.94
MnO	0.07	0.05	0.11	0.04
MgO	0.57	1.03	0.43	1.06
CaO	3.03	0.90	1.58	0.56
Na2O	2.11	1.95	1.75	2.18
K2O	1.49	2.31	0.59	2.23
P2O5	0.02	0.02	0.02	0.12
LOI	3.34	2.33	2.36	2.61
Analytical Total	99.69	100.23	100.50	99.33
al-alk	14.09	22.26	15.24	23.71
nigmg	1.00	1.00	1.00	0.99
nigfm	14.78	21.55	17.13	23.81
nig k	0.32	0.44	0.18	0.40
nigti	0.03	0.03	0.04	0.03
nigsi	626.28	574.91	1010.97	521.72
Fe2O3+MgO	2.68	3.63	1.99	4.94
Al2O3/SiO2	0.10	0.14	0.07	0.16
K2O/Na2O	0.71	1.18	0.34	1.02
Al2O3/(CaO+Na2O)	1.59	3.82	1.73	4.34

Cambrian Sandstones Major Elements

SAMPLE	LQ 83 5A	WF 75 85	MP B1	MP B5
grainsize	crs	crs	crs	crs
structure	mass	mass	mass	mass
SiO2	79.43	75.88	75.67	78.50
TiO2	0.66	0.44	0.64	0.66
Al2O3	9.81	8.59	12.31	10.98
Fe2O3	4.14	2.68	4.35	3.70
MnO	0.05	0.56	0.05	0.05
MgO	0.69	0.70	1.24	0.89
CaO	0.85	7.75	0.91	0.86
Na2O	1.80	2.22	2.14	2.40
K2O	2.48	1.16	2.68	1.92
P2O5	0.08	0.02	0.02	0.02
LOI	2.14	7.43	2.25	1.73
Analytical Total	98.95	98.50	97.72	99.37
al-alk	19.44	11.54	22.34	21.27
nigmg	0.99	1.00	1.00	1.00
nigfm	20.83	13.47	22.68	20.15
nig k	0.48	0.26	0.45	0.34
nigti	0.04	0.02	0.03	0.04
nigsi	628.08	403.36	487.23	572.47
Fe2O3+MgO	4.14	2.68	4.35	3.70
Al2O3/SiO2	0.12	0.11	0.16	0.14
K2O/Na2O	1.38	0.52	1.25	0.80
Al2O3/(CaO+Na2O)	3.71	0.86	4.04	3.37

Cambrian Sandstones Major Elements

SAMPLE	MAID 1	SAB 1	E-WP	IRI 1
grainsize	crs	crs	crs	crs
structure	mass	mass	mass	mass
SiO2	89.96	78.64	93.07	90.73
TiO2	0.46	0.52	0.26	0.20
Al2O3	5.14	10.60	2.94	4.38
Fe2O3	2.44	3.89	1.15	1.86
MnO	0.02	0.17	0.01	0.02
MgO	0.46	1.07	0.34	0.59
CaO	0.26	1.07	1.02	0.75
Na2O	0.30	2.74	0.93	0.97
K2O	0.95	1.28	0.27	0.48
P2O5	0.02	0.02	0.02	0.02
LOI	1.09	2.03	1.22	1.40
Analytical Total	98.34	100.02	99.01	97.96
al-alk	36.71	19.64	13.70	21.42
nigmg	1.00	1.00	1.00	1.00
nigfm	27.90	22.77	19.46	25.68
nig k	0.68	0.24	0.16	0.24
nigti	0.06	0.03	0.04	0.02
nigsi	1545.55	558.72	1921.02	1457.33
Fe2O3+MgO	2.44	3.89	1.15	1.86
Al2O3/SiO2	0.06	0.13	0.03	0.05
K2O/Na2O	3.17	0.47	0.29	0.49
Al2O3/(CaO+Na2O)	9.26	2.78	1.51	2.55

Cambrian Sandstones Major Elements

SAMPLE	HAN B12	HAS B6	LQ 82 163	HAN B5
grainsize	crs	crs	crs	crs
structure	mass	mass	mass	mass
SiO2	89.79	95.27	92.94	73.38
TiO2	0.21	0.16	0.21	0.91
Al2O3	5.05	2.23	2.54	14.48
Fe2O3	1.85	0.01	1.29	4.01
MnO	0.02	0.40	0.02	0.05
MgO	0.67	0.33	0.40	0.61
CaO	0.93	0.49	1.62	0.52
Na2O	0.62	0.08	0.62	2.56
K2O	0.81	0.05	0.27	3.45
P2O5	0.06	0.97	0.08	0.02
LOI	2.11	1.32	2.08	2.03
Analytical Total	99.00	99.02	98.38	99.77
al-alk	27.37	43.21	14.13	23.68
nigmg	0.99	0.77	0.99	1.00
nigfm	25.20	29.83	21.61	15.19
nig k	0.46	0.29	0.22	0.47
nigti	0.02	0.04	0.03	0.04
nigsi	1321.36	3423.60	1816.43	451.71
Fe2O3+MgO	1.85	0.01	1.29	4.01
Al2O3/SiO2	0.06	0.02	0.03	0.20
K2O/Na2O	1.30	0.63	0.43	1.35
Al2O3/(CaO+Na2O)	3.26	3.89	1.13	4.70

Cambrian Sandstones Major Elements

SAMPLE	Saint 1	N 239 G	DB 4	GM 1
grainsize	crs	crs	crs	crs
structure	mass	mass	mass	mass
SiO2	90.38	91.57	97.48	85.67
TiO2	0.73	0.20	0.16	0.44
Al2O3	4.05	4.31	1.12	5.88
Fe2O3	2.02	0.35	0.42	2.82
MnO	0.00	0.00	0.00	0.02
MgO	0.07	0.03	0.08	0.81
CaO	0.00	0.02	0.02	0.46
Na2O	0.07	0.08	0.03	0.36
K2O	2.67	3.43	0.67	3.27
P2O5	0.00	0.01	0.01	0.27
LOI	0.50	0.43	0.48	1.21
Analytical Total	99.20	99.59	99.37	101.01
al-alk	12.19	5.44	14.55	11.90
nigmg	1.00	1.00	0.99	0.97
nigfm	17.26	3.56	19.77	26.34
nig k	0.96	0.97	0.94	0.86
nigti	0.11	0.03	0.09	0.04
nigsi	1798.43	1830.66	6871.97	987.12
Fe2O3+MgO	2.02	0.35	0.42	2.82
Al2O3/SiO2	0.04	0.05	0.01	0.07
K2O/Na2O	37.71	42.50	22.00	9.06
Al2O3/(CaO+Na2O)	57.14	42.70	22.20	7.16

Cambrian Sandstones Major Elements

SAMPLE	HB 6
grainsize	crs
structure	mass
SiO2	97.11
TiO2	0.04
Al2O3	0.77
Fe2O3	0.73
MnO	0.01
MgO	0.17
CaO	0.04
Na2O	0.02
K2O	0.44
P2O5	0.02
LOI	0.40
Analytical Total	99.02
al-alk	9.27
nigmg	0.99
nigfm	50.44
nig k	0.94
nigti	0.02
nigsi	6042.80
Fe2O3+MgO	1.38
Al2O3/SiO2	0.01
K2O/Na2O	22.00
Al2O3/(CaO+Na2O)	12.67

Cambrian Trace Elements

Element	BMD 2	W1 B3	WF-76-85	BMD 8	LQ 83 5A
Ba	363	425	139	676	427.77
Sr	82	83	63	73	70
Zr	293	294	316	354	383
Y	14	14	10	21	15
Be	<1	<1	<1	n/a	n/a
Cu	45	15	5	12	16
Ni	10	20	10	29	26
Pb	<50	<50	<50	30	20
V	24	36	16	50	47
Zn	90	70	50	63	42
Ag	0.3	0.1	0.1	n/a	n/a
Nb	<30	<30	<30	12	13
Au	41	<5	5	n/a	n/a
As	<2	<2	3	n/a	n/a
Br	<1	<1	<1	n/a	n/a
Co	5	10	4	54	38
Cr	40	55	27	37	42
Cs	1.6	1.3	<0.5	n/a	n/a
Hf	6.6	7.4	6.7	8.505	7.521
Hg	<1	<1	<1	n/a	n/a
Ir	<5	<5	<5	n/a	n/a
Mo	<5	<5	<5	n/a	n/a
Rb	65	93	<20	62	74
Sb	4.6	0.4	0.6	n/a	n/a
Sc	5.5	6.2	2.4	5	4
Se	<3	<3	<3	n/a	n/a
Ta	<1	<1	<1	1.048	0.697
Th	7.7	8.5	6.9	15	6
U	0.7	2	1	0	<1
W	<3	<3	<3	n/a	n/a
La	19	21.9	19.4	28.974	26.921
Ce	45	52	45	59.715	55.395
Nd	21	23	17	26.476	23.677
Sm	2.8	3.5	2.6	5.315	4.0145
Eu	0.7	0.9	0.6	1.197	0.729
Tb	0.5	<0.5	<0.5	0.661	0.437
Yb	1.1	1.5	0.8	2.039	1.729
Lu	0.17	0.2	0.15	0.329	0.28
LaN/YbN	10.60	7.77	14.57	5.72	6.74
La/Yb	17.27	14.60	24.25	14.21	15.57
La/Sm	6.79	6.26	7.46	5.45	6.71
Hf/Yb	6.00	4.93	8.38	4.17	4.35

Cambrian Trace Elements

Element	WF 75 85	MP B1	MP B5	MAID 1	SAB 1
Ba	361	720	501	282	319
Sr	178	120	92	24	102
Zr	297	304	411	327	227
Y	16	12	14	8	12
Be	n/a	<1	<1	<1	<1
Cu	8	35	30	20	20
Ni	18	20	10	10	10
Pb	16	<50	<50	<50	<50
V	31	46	34	22	30
Zn	31	120	120	65	85
Ag	n/a	0.1	1.9	0.4	0.2
Nb	6	<30	<30	<30	<30
Au	n/a	12	260	7	5
As	n/a	2	4	3	<2
Br	n/a	<1	<1	<1	<1
Co	51	13	9	4	10
Cr	32	64	57	35	48
Cs	n/a	2.6	1.3	<0.5	<0.5
Hf	8.892	7.9	9.1	8.7	6.1
Hg	n/a	<1	<1	<1	<1
Ir	n/a	<5	<5	<5	<5
Mo	n/a	<5	<5	<5	<5
Rb	35	93	67	37	39
Sb	n/a	8.9	17	3.6	1.6
Sc	6	6.9	6	3	5.4
Se	n/a	<3	<3	<3	<3
Ta	1.399	1	<1	<1	<1
Th	13	9.5	9.3	8.8	7.5
U	0	1.6	1.5	1.4	1.2
W	n/a	<3	<3	<3	<3
La	20.537	27.2	24.9	21.4	22.3
Ce	44.828	63	58	47	50
Nd	17.771	23	23	15	20
Sm	3.4985	3.8	3.8	2.1	3.3
Eu	0.895	0.9	0.9	0.5	0.8
Tb	0.448	0.5	0.6	0.5	0.5
Yb	1.256	1.3	1.5	0.9	1.3
Lu	0.197	0.25	0.23	0.17	0.22
LaN/YbN	9.28	8.97	7.77	12.95	8.97
La/Yb	16.35	20.92	16.60	23.78	17.15
La/Sm	5.87	7.16	6.55	10.19	6.76
Hf/Yb	7.08	6.08	6.07	9.67	4.69

Cambrian Trace Elements

Element	E-WP	IRI 1	HAN B12	HAS B6	LQ 82 163
Ba	90	109	263	73	106
Sr	57	28	29	14	30
Zr	304	231	235	236	254
Y	8	6	7	5	4
Be	<1	<1	n/a	n/a	n/a
Cu	65	5	6	6	5
Ni	10	10	11	5	7
Pb	<50	<50	5	5	5
V	12	14	20	10	11
Zn	75	65	17	14	13
Ag	1.3	0.6	n/a	n/a	n/a
Nb	<30	<30	5	3	3
Au	66	11	n/a	n/a	n/a
As	4	<2	n/a	n/a	n/a
Br	<1	<1	n/a	n/a	n/a
Co	3	4	133	207	164
Cr	31	25	23	12	5
Cs	<0.5	<0.5	n/a	n/a	n/a
Hf	6.5	5	4.892	4.571	6.883
Hg	<1	<1	n/a	n/a	n/a
Ir	<5	<5	n/a	n/a	n/a
Mo	<5	<5	n/a	n/a	n/a
Rb	<20	22	30	5	10
Sb	14	4.7	n/a	n/a	n/a
Sc	2	2.1	n/a	n/a	n/a
Se	<3	<3	n/a	n/a	n/a
Ta	<1	<1	2.241	3.086	2.321
Th	2.9	2.3	4	4	3
U	1.4	0.6	0	0	2
W	<3	<3	n/a	n/a	n/a
La	9.3	8.9	13.995	8.505	7.261
Ce	24	23	29.607	17.97	15.037
Nd	10	8	12.22	7.618	6.22
Sm	1.6	1.5	2.11	1.368	1.286
Eu	0.5	0.4	0.477	0.276	0.31
Tb	<0.5	<0.5	0.236	0.143	0.136
Yb	0.7	0.5	0.83	0.573	0.591
Lu	0.13	0.09	0.136	0.085	0.086
LaN/YbN	16.65	23.31	14.04	20.34	19.72
La/Yb	13.29	17.80	16.86	14.84	12.29
La/Sm	5.81	5.93	6.63	6.22	5.65
Hf/Yb	9.29	10.00	5.89	7.98	11.65

Cambrian Trace Elements

Element	HAN B5	SAINT 1	N239G	DB 4	GM 1
Ba	721	381	663	179	869
Sr	78	34	74	11	87
Zr	685	445	100	379	680
Y	18	7	3	7	27
Be	<1	n/a	n/a	n/a	n/a
Cu	30	5	5	58	18
Ni	10	9	5	5	17
Pb	<50	5	5	5	9
V	26	34	7	8	27
Zn	75	5	5	5	20
Ag	0.3	n/a	n/a	n/a	n/a
Nb	<30	15	3	2	10
Au	7	n/a	n/a	n/a	n/a
As	11	n/a	n/a	n/a	n/a
Br	<1	n/a	n/a	n/a	n/a
Co	7	169	333	124	76
Cr	24	19	5	1	40
Cs	2.3	n/a	n/a	n/a	n/a
Hf	16	3.12	1.183	4.707	12.706
Hg	<1	n/a	n/a	n/a	n/a
Ir	<5	n/a	n/a	n/a	n/a
Mo	<5	n/a	n/a	n/a	n/a
Rb	100	55	54	11	46
Sb	3.2	n/a	n/a	n/a	n/a
Sc	5.6	n/a	n/a	n/a	n/a
Se	<3	n/a	n/a	n/a	n/a
Ta	<1	1.751	3.572	1.104	0.95
Th	8.7	5	5	6	8
U	1.6	3	0	2	1
W	<3	n/a	n/a	n/a	n/a
La	23.6	10.797	13.21	4.26	16.961
Ce	55	20.843	26.958	9.371	45.889
Nd	26	7.666	8.36	3.234	20.843
Sm	4.7	1.2655	1.122	0.6915	5.0265
Eu	1.3	0.285	0.262	0.192	1.27
Tb	0.7	0.17	0.066	0.151	0.802
Yb	2	0.756	0.349	0.347	2.45
Lu	0.32	0.115	0.062	0.141	0.391
LaN/YbN	5.83	15.42	33.40	13.76	4.76
La/Yb	11.80	14.28	37.85	5.03	6.92
La/Sm	5.02	8.53	11.77	6.16	3.37
Hf/Yb	8.00	4.13	3.39	5.56	5.19

Cambrian Trace Elements

Element	HB 6
Ba	120
Sr	6
Zr	136
Y	4
Be	n/a
Cu	6
Ni	5
Pb	5
V	5
Zn	5
Ag	n/a
Nb	1
Au	n/a
As	n/a
Br	n/a
Co	191
Cr	5
Cs	n/a
Hf	2.286
Hg	n/a
Ir	n/a
Mo	n/a
Rb	5
Sb	n/a
Sc	n/a
Se	n/a
Ta	2.923
Th	3
U	0
W	n/a
La	7.012
Ce	5.609
Nd	5.393
Sm	0.906
Eu	0.143
Tb	0.06
Yb	0.354
Lu	0.061
LaN/YbN	32.93
La/Yb	19.81
La/Sm	7.74
Hf/Yb	6.46

Miscellaneous Major Elements

SAMPLE	WH 1	CB 10	CB 11	CB B1	CR B2
SiO2	74.61	81.65	65.64	39.39	85.30
TiO2	0.52	0.17	0.70	2.64	0.02
Al2O3	6.31	9.23	11.76	13.95	0.88
Fe2O3	1.77	1.23	3.81	10.29	0.26
MnO	0.07	0.03	0.23	0.25	0.01
MgO	1.64	1.32	2.24	2.40	0.08
CaO	11.43	1.10	9.80	24.22	12.77
Na2O	1.51	2.73	3.59	3.31	0.37
K2O	1.97	2.53	2.08	2.38	0.27
P2O5	0.18	0.02	0.15	1.16	0.02
LOI	10.10	1.39	8.52	17.09	8.83
TOTAL	100.41	99.96	99.87	99.56	96.16

SAMPLE	NWA 10	NWA 12	TP 5	TP B3	TP B7
SiO2	68.21	71.12	64.55	73.61	63.89
TiO2	0.63	0.62	0.29	0.53	0.30
Al2O3	9.69	10.47	6.61	9.03	6.76
Fe2O3	4.76	5.40	3.81	5.73	3.92
MnO	0.31	0.15	0.19	0.12	0.19
MgO	3.34	3.97	3.05	3.89	3.03
CaO	9.43	4.75	19.07	4.03	19.26
Na2O	2.17	1.76	0.86	1.81	0.95
K2O	1.42	1.72	1.55	1.21	1.49
P2O5	0.04	0.04	0.02	0.04	0.21
LOI	9.17	6.03	14.64	5.50	14.46
TOTAL	100.56	100.22	98.42	100.05	99.07

Miscellaneous Trace Elements

SAMPLE	NWA 10	NWA 12	TP 5	TP B3	TP B7
Ba	407	432	393	267	316
Sr	186	184	456	141	463
Zr	261	249	82	130	69
Y	16	16	20	12	22
Be	<1	<1	<1	<1	<1
Cu	30	35	20	30	30
Ni	110	130	20	140	30
Pb	<50	<50	<50	<50	<50
V	64	60	40	70	40
Zn	85	95	75	75	75
Ag	0.1	0.2	0.1	0.1	0.1
Nb	<30	<30	<30	<30	<30
Au	17	9	<5	<5	6
As	3	4	9	<2	9
Br	<1	<1	<1	<1	<1
Co	15	18	9	18	10
Cr	440	380	120	510	120
Cs	<0.5	2.3	1.5	1.6	1.2
Hf	5.7	4.9	2.3	4	2.2
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	23	<5	33
Rb	30	56	35	53	26
Sb	3.1	4.5	2.1	0.6	1.9
Sc	11	9.8	5.4	11	5.4
Se	<3	<3	<3	<3	<3
Ta	<1	1	<1	<1	<1
Th	5.9	5.9	4.9	4.2	4.5
U	1.7	1.8	2	1.1	1.4
W	<3	<3	<3	<3	<3
La	17.5	18.8	16.4	10.9	16.3
Ce	43	46	40	26	41
Nd	17	21	18	12	16
Sm	3.2	3.4	3.6	2.3	3.9
Eu	0.7	0.6	0.9	0.6	0.9
Tb	0.6	0.5	0.6	<0.5	0.7
Yb	1.6	1.5	1.3	1.1	1.5
Lu	0.26	0.24	0.22	0.2	0.25

A 5.10

Miscellaneous Trace Elements

SAMPLE	WH 1	CB 10	CB 11	CB B1	CR B2
Ba	285	750	570	573	40226
Sr	103	350	200	338	893
Zr	341	85	208	136	40
Y	24	8	28	36	4
Be	<1	<1	<1	2	<1
Cu	15	5	20	10	5
Ni	20	20	50	10	10
Pb	<50	<50	<50	<50	<50
V	14	28	66	52	2
Zn	10	70	65	110	90
Ag	0.1	0.5	0.9	0.1	0.5
Nb	<30	<30	<30	<30	<30
Au	<5	10	<5	7	32
As	2	3	5	6	<2
Br	8	2	<1	<1	1
Co	5	4	12	16	<1
Cr	330	420	350	44	120
Cs	<0.5	<0.5	1.7	<0.5	<0.5
Hf	7.8	2	5.3	7.2	1.6
Hg	<1	<1	<1	<1	<1
Ir	<5	<5	<5	<5	<5
Mo	<5	<5	<5	<5	<5
Rb	37	<20	<20	<20	<20
Sb	0.9	5.3	4.9	3.6	6.5
Sc	4.5	5.9	11	9.1	0.4
Se	<3	<3	<3	<3	<3
Ta	<1	<1	<1	4	<1
Th	6.1	3.3	5.2	6	0.9
U	1.6	<0.5	1.3	1.1	<0.5
W	<3	<3	<3	<3	<3
La	18.2	12.6	19.7	54.8	3.2
Ce	54	30	58	123	7
Nd	25	14	30	57	<5
Sm	5	2	5.7	9.9	0.5
Eu	1.2	0.6	1.4	2.9	<0.2
Tb	0.9	0.5	0.8	1.2	<0.5
Yb	2.2	0.8	2.2	3.1	0.2
Lu	0.35	0.14	0.31	0.46	<0.05

APPENDIX 6 STATISTICS

This appendix includes reformatted tables outputted from SAS/STAT v. 6.03 statistical software package. It includes for the Goose Tickle group and the Lower Head Formation, means and standard deviations for Niggli parameters and trace elements, maximum and minimum values for the same parameters, and correlation matrices.

The factor analysis outputs include two analyses for each unit, one including Niggli (major element) parameters and the other including only trace element parameters. Note that the unrotated factor pattern, the amount of variance explained by each factor, and the rotated factor pattern are all included. Calculation of eigenvalues and partial correlations are steps in the factor analysis process, as are prior communality estimates (see Davis, 1986 and SAS/STAT users guide, 1988 for more details of the method).

The most important feature in evaluating the quality of the analysis is Kaiser's measure of sampling adequacy, which should be >0.5 for all individual values and overall. Clearly none of the analyses can be considered ideal, probably because of the relatively small number of samples involved. In particular, the Lower Head Formation data must be considered unsuitable for factor analysis.

Goose Tickle Correlation Matrix
Means and Standard Deviations

Variable	N	Mean	Std Dev	Sum
al-alk	42	9.54	3.59	400.75
NIG Ti	42	1.52	0.59	63.95
NIG Fm	42	29.88	8.04	1255.00
NIG K	42	0.44	0.07	18.27
NIG Mg	42	0.62	0.06	26.25
NIG Si	42	290.04	110.61	12182.00
CaO	42	9.65	6.06	405.36
K_2O	42	1.43	0.49	60.01
Ba	42	670.88	1194.00	28177.00
Sr	42	183.00	89.12	7686.00
Zr	42	197.93	129.69	8313.00
Y	42	18.98	4.68	797.00
Cu	42	27.64	11.83	1161.00
Ni	42	117.14	52.34	4920.00
V	42	50.62	14.19	2126.00
Zn	42	85.86	25.28	3606.00
Ag	37	0.26	0.37	9.50
Au	37	16.24	22.48	601.00
As	37	6.22	3.63	230.00
Co	42	18.24	8.28	766.00
Cr	42	441.38	339.05	18538.00
Cs	37	1.46	0.72	54.10
Hf	42	4.68	3.10	196.75
Pb	42	44.81	18.34	1882.00
Sb	37	3.70	4.27	136.90
Sc	42	8.03	2.54	337.20
Th	42	5.33	2.13	224.00
U	39	1.73	0.72	67.30
La	42	18.26	5.29	767.08
Ce	42	43.78	12.51	1839.00
Nd	42	19.20	5.13	806.30
Sm	42	3.59	0.91	150.70
Eu	42	0.81	0.21	33.81
Tb	42	0.58	0.13	24.53
Yb	42	1.51	0.48	63.21
Lu	42	0.24	0.09	9.94

Minima and Maxima

Variable	Minimum	Maximum
al-alk	2.46	17.32
NIG Ti	0.38	2.57
NIG Fm	10.86	42.76
NIG K	0.26	0.61
NIG Mg	0.50	0.83
NIG Si	66.40	525.87
CaO	3.08	29.90
K_2O	0.74	2.66
Ba	143.00	6964.00
Sr	73.00	488.00
Zr	49.00	610.00
Y	12.00	30.00
Cu	9.00	70.00
Ni	10.00	260.00
V	14.00	75.00
Zn	32.00	140.00
Ag	0.10	2.10
Au	5.00	115.00
As	2.00	18.00
Co	6.00	46.00
Cr	48.00	1440.00
Cs	0.50	3.30
Hf	1.40	16.00
Rb	20.00	79.00
Sb	0.80	23.00
Sc	3.40	14.00
Th	2.60	11.00
U	0.50	4.00
La	10.20	29.80
Ce	24.00	70.00
Nd	11.54	31.00
Sm	2.10	5.30
Eu	0.40	1.20
Tb	0.31	0.90
Yb	0.80	2.80
Lu	0.13	0.48

Correlation Coefficients

	al-alk	NIG Ti	NIG Fm	NIG K	NIG Mg	NIG Si
al-alk	1.00	0.81	0.72	0.33	-0.26	0.37
NIG Ti	0.81	1.00	0.47	0.23	-0.38	0.21
NIG Fm	0.72	0.47	1.00	0.09	0.37	0.27
NIG K	0.33	0.23	0.09	1.00	-0.29	0.20
NIG Mg	-0.26	-0.38	0.37	-0.29	1.00	-0.33
NIG Si	0.37	0.21	0.27	0.20	-0.33	1.00
CaO	-0.80	-0.65	-0.66	-0.20	0.29	-0.75
K_2O	0.73	0.74	0.32	0.41	-0.33	-0.09
Ba	-0.17	-0.14	-0.26	-0.17	0.04	-0.36
Sr	-0.47	-0.37	-0.29	-0.53	0.44	-0.63
Zr	0.51	0.78	0.27	0.21	-0.26	-0.07
Y	0.13	0.42	-0.05	0.20	-0.09	-0.56
Cu	0.54	0.48	0.54	0.05	-0.07	0.11
Ni	0.33	0.25	0.48	-0.02	0.03	0.35
V	0.66	0.62	0.40	0.34	-0.21	-0.05
Zn	0.44	0.43	0.40	-0.10	-0.14	0.21
Ag	-0.15	-0.16	0.02	-0.10	0.12	0.00
Au	-0.26	-0.18	-0.18	0.02	-0.02	0.32
As	-0.02	0.02	0.13	-0.01	0.00	0.31
Co	0.40	0.23	0.35	0.13	-0.01	0.11
Cr	0.01	0.16	0.09	-0.06	-0.04	0.19
Cs	0.59	0.60	0.38	0.16	0.05	-0.35
Hf	0.50	0.76	0.24	0.22	-0.24	-0.09
Rb	0.66	0.59	0.37	0.24	-0.23	-0.16
Sb	-0.16	-0.22	0.07	-0.17	0.18	-0.03
Sc	0.41	0.41	0.40	0.15	0.17	-0.28
Th	0.63	0.73	0.27	0.37	-0.31	-0.19
U	0.72	0.69	0.41	0.45	-0.35	0.10
La	0.52	0.70	0.17	0.37	-0.25	-0.33
Ce	0.56	0.76	0.24	0.32	-0.23	-0.27
Nd	0.54	0.68	0.22	0.33	-0.18	-0.23
Sm	0.47	0.66	0.25	0.22	-0.08	-0.35
Eu	0.45	0.72	0.19	0.09	-0.17	-0.27
Tb	0.21	0.48	0.09	0.08	-0.10	-0.36
Yb	0.43	0.68	0.25	0.17	-0.08	-0.37
Lu	0.46	0.71	0.24	0.20	-0.15	-0.33

Correlation Coefficients (cont.)

	CaO	K_2O	Ba	Sr	Zr	Y
al-alk	-0.80	0.73	-0.17	-0.47	0.51	0.13
NIG Ti	-0.65	0.74	-0.14	-0.37	0.78	0.42
NIG Fm	-0.66	0.32	-0.26	-0.29	0.27	-0.05
NIG K	-0.20	0.41	-0.17	-0.53	0.21	0.20
NIG Mg	0.29	-0.33	0.04	0.44	-0.26	-0.09
NIG Si	-0.75	-0.09	-0.36	-0.63	-0.07	-0.56
CaO	1.00	-0.42	0.37	0.66	-0.32	0.27
K_2O	-0.42	1.00	0.01	-0.35	0.63	0.50
Ba	0.37	0.01	1.00	0.34	-0.05	0.15
Sr	0.66	-0.35	0.34	1.00	-0.15	0.16
Zr	-0.32	0.63	-0.05	-0.15	1.00	0.63
Y	0.27	0.50	0.15	0.16	0.63	1.00
Cu	-0.46	0.32	-0.17	-0.10	0.37	0.12
Ni	-0.45	-0.16	-0.24	-0.13	0.13	-0.19
V	-0.32	0.53	0.07	-0.19	0.43	0.36
Zn	-0.46	0.25	-0.26	-0.03	0.44	0.13
Ag	-0.03	-0.03	0.07	0.05	-0.08	-0.12
Au	-0.06	-0.20	-0.01	-0.05	-0.14	-0.31
As	-0.20	-0.25	-0.23	-0.19	0.00	0.00
Co	-0.26	0.18	-0.10	-0.18	0.06	0.12
Cr	-0.11	-0.35	-0.28	0.12	0.17	-0.09
Cs	-0.24	0.76	0.13	-0.08	0.46	0.55
Hf	-0.29	0.62	-0.01	-0.11	0.99	0.64
Rb	-0.36	0.88	-0.04	-0.26	0.52	0.42
Sb	-0.01	-0.09	0.10	0.10	-0.15	-0.20
Sc	-0.11	0.34	0.04	0.09	0.33	0.35
Th	-0.27	0.84	0.06	-0.23	0.77	0.66
U	-0.55	0.75	-0.25	-0.52	0.62	0.48
La	-0.10	0.83	0.15	-0.13	0.74	0.85
Ce	-0.19	0.82	0.07	-0.13	0.80	0.83
Nd	-0.18	0.82	0.10	-0.12	0.74	0.77
Sm	-0.08	0.74	0.07	-0.01	0.72	0.87
Eu	-0.17	0.68	-0.02	0.06	0.70	0.73
Tb	0.03	0.47	-0.09	0.09	0.61	0.75
Yb	-0.09	0.70	0.04	0.00	0.89	0.85
Lu	-0.14	0.71	0.01	-0.03	0.91	0.82

Correlation Coefficients (cont.)

	Cu	Ni	V	Zn	Ag	Au
al-alk	0.54	0.33	0.66	0.44	-0.15	-0.26
NIG Ti	0.48	0.25	0.62	0.43	-0.16	-0.18
NIG Fm	0.54	0.48	0.40	0.40	0.02	-0.18
NIG K	0.05	-0.02	0.34	-0.10	-0.10	0.02
NIG Mg	-0.07	0.03	-0.21	-0.14	0.12	-0.02
NIG Si	0.11	0.35	-0.05	0.21	0.00	0.32
CaO	-0.46	-0.45	-0.32	-0.46	-0.03	-0.06
K_2O	0.32	-0.16	0.53	0.25	-0.03	-0.20
Ba	-0.17	-0.24	0.07	-0.26	0.07	-0.01
Sr	-0.10	-0.13	-0.19	-0.03	0.05	-0.05
Zr	0.37	0.13	0.43	0.44	-0.08	-0.14
Y	0.12	-0.19	0.36	0.13	-0.12	-0.31
Cu	1.00	0.39	0.31	0.64	0.00	-0.18
Ni	0.39	1.00	0.40	0.29	-0.07	-0.06
V	0.31	0.40	1.00	0.03	-0.17	-0.26
Zn	0.64	0.29	0.03	1.00	0.03	-0.15
Ag	0.00	-0.07	-0.17	0.03	1.00	0.56
Au	-0.18	-0.06	-0.26	-0.15	0.56	1.00
As	0.04	0.40	-0.04	0.12	0.43	0.23
Co	0.11	0.38	0.65	-0.10	-0.18	-0.17
Cr	0.34	0.69	0.19	0.22	-0.20	0.05
Cs	0.34	-0.19	0.44	0.18	0.01	-0.18
Hf	0.37	0.11	0.44	0.41	-0.10	-0.14
Rb	0.37	-0.16	0.40	0.27	0.00	-0.20
Sb	0.05	0.02	-0.14	0.05	0.93	0.59
Sc	0.34	0.47	0.80	0.00	-0.22	-0.31
Th	0.25	-0.05	0.63	0.20	-0.05	-0.16
U	0.19	-0.08	0.52	0.26	-0.18	-0.18
La	0.25	-0.15	0.55	0.20	-0.13	-0.24
Ce	0.33	-0.10	0.47	0.36	-0.15	-0.28
Nd	0.31	-0.17	0.38	0.34	-0.12	-0.25
Sm	0.30	-0.21	0.40	0.35	-0.16	-0.34
Eu	0.37	-0.04	0.40	0.40	-0.22	-0.36
Tb	0.36	-0.15	0.13	0.41	-0.03	-0.18
Yb	0.32	-0.09	0.42	0.36	-0.11	-0.29
Lu	0.36	-0.04	0.44	0.38	-0.12	-0.27

Correlation Coefficients (cont.)

	As	Co	Cr	Cs	Hf	Rb
al-alk	-0.02	0.40	0.01	0.59	0.50	0.66
NIG Ti	0.02	0.23	0.16	0.60	0.76	0.59
NIG Fm	0.13	0.35	0.09	0.38	0.24	0.37
NIG K	-0.01	0.13	-0.06	0.16	0.22	0.24
NIG Mg	0.00	-0.01	-0.04	0.05	-0.24	-0.23
NIG Si	0.31	0.11	0.19	-0.35	-0.09	-0.16
CaO	-0.20	-0.26	-0.11	-0.24	-0.29	-0.36
K_2O	-0.25	0.18	-0.35	0.76	0.62	0.88
Ba	-0.23	-0.10	-0.28	0.13	-0.01	-0.04
Sr	-0.19	-0.18	0.12	-0.08	-0.11	-0.26
Zr	0.00	0.06	0.17	0.46	0.99	0.52
Y	0.00	0.12	-0.09	0.55	0.64	0.42
Cu	0.04	0.11	0.34	0.34	0.37	0.37
Ni	0.40	0.38	0.69	-0.19	0.11	-0.16
V	-0.04	0.65	0.19	0.44	0.44	0.40
Zn	0.12	-0.10	0.22	0.18	0.41	0.27
Ag	0.43	-0.18	-0.20	0.01	-0.10	0.00
Au	0.23	-0.17	0.05	-0.18	-0.14	-0.20
As	1.00	0.30	0.29	-0.15	-0.03	-0.22
Co	0.30	1.00	0.16	0.17	0.07	0.14
Cr	0.29	0.16	1.00	-0.39	0.17	-0.40
Cs	-0.15	0.17	-0.39	1.00	0.47	0.69
Hf	-0.03	0.07	0.17	0.47	1.00	0.51
Rb	-0.22	0.14	-0.40	0.69	0.51	1.00
Sb	0.39	-0.11	-0.15	-0.04	-0.16	0.01
Sc	-0.05	0.59	0.29	0.42	0.36	0.29
Th	-0.10	0.34	-0.16	0.72	0.79	0.73
U	-0.09	0.49	-0.23	0.58	0.58	0.68
La	-0.11	0.20	-0.19	0.76	0.76	0.70
Ce	-0.10	0.08	-0.13	0.75	0.81	0.69
Nd	-0.17	0.00	-0.25	0.70	0.74	0.71
Sm	-0.12	0.10	-0.21	0.71	0.72	0.65
Eu	-0.19	0.04	-0.03	0.55	0.69	0.57
Tb	0.05	-0.15	-0.07	0.51	0.57	0.51
Yb	-0.08	0.09	-0.08	0.64	0.88	0.63
Lu	-0.10	0.06	-0.01	0.63	0.91	0.63

Correlation Coefficients (cont.)

	Sb	Sc	Th	U	La	Ce
al-alk	-0.16	0.41	0.63	0.72	0.52	0.56
NIG Ti	-0.22	0.41	0.73	0.69	0.70	0.76
NIG Fm	0.07	0.40	0.27	0.41	0.17	0.24
NIG K	-0.17	0.15	0.37	0.45	0.37	0.32
NIG Mg	0.18	0.17	-0.31	-0.35	-0.25	-0.23
NIG Si	-0.03	-0.28	-0.19	0.10	-0.33	-0.27
CaO	-0.01	-0.11	-0.27	-0.55	-0.10	-0.19
K_2O	-0.09	0.34	0.84	0.75	0.83	0.82
Ba	0.10	0.04	0.06	-0.25	0.15	0.07
Sr	0.10	0.09	-0.23	-0.52	-0.13	-0.13
Zr	-0.15	0.33	0.77	0.62	0.74	0.80
Y	-0.20	0.35	0.66	0.48	0.85	0.83
Cu	0.05	0.34	0.25	0.19	0.25	0.33
Ni	0.02	0.47	-0.05	-0.08	-0.15	-0.10
V	-0.14	0.80	0.63	0.52	0.55	0.47
Zn	0.05	0.00	0.20	0.26	0.20	0.36
Ag	0.93	-0.22	-0.05	-0.18	-0.13	-0.15
Au	0.59	-0.31	-0.16	-0.18	-0.24	-0.28
As	0.39	-0.05	-0.10	-0.09	-0.11	-0.10
Co	-0.11	0.59	0.34	0.49	0.20	0.08
Cr	-0.15	0.29	-0.16	-0.23	-0.19	-0.13
Cs	-0.04	0.42	0.72	0.58	0.76	0.75
Hf	-0.16	0.36	0.79	0.58	0.76	0.81
Rb	0.01	0.29	0.73	0.68	0.70	0.69
Sb	1.00	-0.15	-0.10	-0.25	-0.20	-0.23
Sc	-0.15	1.00	0.43	0.21	0.41	0.35
Th	-0.10	0.43	1.00	0.81	0.90	0.86
U	-0.25	0.21	0.81	1.00	0.73	0.70
La	-0.20	0.41	0.90	0.73	1.00	0.97
Ce	-0.23	0.35	0.86	0.70	0.97	1.00
Nd	-0.22	0.24	0.80	0.68	0.92	0.95
Sm	-0.24	0.31	0.79	0.68	0.92	0.96
Eu	-0.26	0.35	0.67	0.48	0.76	0.85
Tb	-0.12	0.15	0.46	0.44	0.63	0.71
Yb	-0.18	0.40	0.82	0.63	0.89	0.92
Lu	-0.19	0.40	0.82	0.64	0.87	0.91

Correlation Coefficients (cont.)

	Nd	Sm	Eu	Tb	Yb	Lu
al-alk	0.54	0.47	0.45	0.21	0.43	0.46
NIG Ti	0.68	0.66	0.72	0.48	0.68	0.71
NIG Fm	0.22	0.25	0.19	0.09	0.25	0.24
NIG K	0.33	0.22	0.09	0.08	0.17	0.20
NIG Mg	-0.18	-0.08	-0.17	-0.10	-0.08	-0.15
NIG Si	-0.23	-0.35	-0.27	-0.36	-0.37	-0.33
CaO	-0.18	-0.08	-0.17	0.03	-0.09	-0.14
K_2O	0.82	0.74	0.68	0.47	0.70	0.71
Ba	0.10	0.07	-0.02	-0.09	0.04	0.01
Sr	-0.12	-0.01	0.06	0.09	0.00	-0.03
Zr	0.74	0.72	0.70	0.61	0.89	0.91
Y	0.77	0.87	0.73	0.75	0.85	0.82
Cu	0.31	0.30	0.37	0.36	0.32	0.36
Ni	-0.17	-0.21	-0.04	-0.15	-0.09	-0.04
V	0.38	0.40	0.40	0.13	0.42	0.44
Zn	0.34	0.35	0.40	0.41	0.36	0.38
Ag	-0.12	-0.16	-0.22	-0.03	-0.11	-0.12
Au	-0.25	-0.34	-0.36	-0.18	-0.29	-0.27
As	-0.17	-0.12	-0.19	0.05	-0.08	-0.10
Co	0.00	0.10	0.04	-0.15	0.09	0.06
Cr	-0.25	-0.21	-0.03	-0.07	-0.08	-0.01
Cs	0.70	0.71	0.55	0.51	0.64	0.63
Hf	0.74	0.72	0.69	0.57	0.88	0.91
Rb	0.71	0.65	0.57	0.51	0.63	0.63
Sb	-0.22	-0.24	-0.26	-0.12	-0.18	-0.19
Sc	0.24	0.31	0.35	0.15	0.40	0.40
Th	0.80	0.79	0.67	0.46	0.82	0.82
U	0.68	0.68	0.48	0.44	0.63	0.64
La	0.92	0.92	0.76	0.63	0.89	0.87
Ce	0.95	0.96	0.85	0.71	0.92	0.91
Nd	1.00	0.93	0.82	0.67	0.86	0.85
Sm	0.93	1.00	0.84	0.74	0.92	0.89
Eu	0.82	0.84	1.00	0.68	0.81	0.80
Tb	0.67	0.74	0.68	1.00	0.76	0.74
Yb	0.86	0.92	0.81	0.76	1.00	0.98
Lu	0.85	0.89	0.80	0.74	0.98	1.00

A 6.2

Lower Head Formation
Correlation Statistics
Means and Standard Deviations

Variable	N	Mean	Std Dev	Sum
al-alk	34	11.82	3.41	401.84
NIG Ti	34	2.03	0.61	69.05
NIG Fm	34	32.81	9.36	1116.00
NIG K	34	0.39	0.08	13.22
NIG Mg	34	0.60	0.04	20.36
NIG Si	34	365.67	100.83	12433.00
CaO	34	5.72	4.28	194.46
K_2O	34	1.56	0.40	52.95
Ba	34	441.82	194.74	15022.00
Sr	34	121.35	42.44	4126.00
Zr	34	261.47	196.19	8890.00
Y	34	16.85	4.89	573.00
Cu	34	25.41	13.82	864.00
Ni	34	103.18	31.63	3508.00
V	34	55.68	15.77	1893.00
Zn	34	74.56	15.74	2535.00
Ag	31	0.18	0.22	5.70
Ag	31	7.74	6.25	240.00
As	31	3.61	2.01	112.00
Co	34	15.97	8.16	543.00
Cr	34	337.76	174.92	11484.00
Cs	31	1.25	0.90	38.60
Hf	34	6.18	4.31	210.11
Rb	34	50.47	18.69	1716.00
Sb	31	2.39	2.72	74.20
Sc	34	8.39	2.53	285.30
Th	34	6.24	2.99	212.30
U	32	1.61	0.51	51.60
La	34	18.49	6.11	628.49
Ce	34	43.44	13.52	1477.00
Nd	34	17.87	5.39	607.42
Sm	34	3.23	0.87	109.92
Eu	34	0.75	0.17	25.61
Tb	34	0.55	0.11	18.77
Yb	34	1.53	0.42	52.05
Lu	34	0.24	0.07	8.31

Lower Head Formation
Correlation Statistics
Means and Standard Deviations

Variable	N	Mean	Std Dev	Sum
al-alk	34	11.82	3.41	401.84
NIG Ti	34	2.03	0.61	69.05
NIG Fm	34	32.81	9.36	1116.00
NIG K	34	0.39	0.08	13.22
NIG Mg	34	0.60	0.04	20.36
NIG Si	34	365.67	100.83	12433.00
CaO	34	5.72	4.28	194.46
K_2O	34	1.56	0.40	52.95
Ba	34	441.82	194.74	15022.00
Sr	34	121.35	42.44	4126.00
Zr	34	261.47	196.19	8890.00
Y	34	16.85	4.89	573.00
Cu	34	25.41	13.82	864.00
Ni	34	103.18	31.63	3508.00
V	34	55.68	15.77	1893.00
Zn	34	74.56	15.74	2535.00
Ag	31	0.18	0.22	5.70
Ag	31	7.74	6.25	240.00
As	31	3.61	2.01	112.00
Co	34	15.97	8.16	543.00
Cr	34	337.76	174.92	11484.00
Cs	31	1.25	0.90	38.60
Hf	34	6.18	4.31	210.11
Rb	34	50.47	18.69	1716.00
Sb	31	2.39	2.72	74.20
Sc	34	8.39	2.53	285.30
Th	34	6.24	2.99	212.30
U	32	1.61	0.51	51.60
La	34	18.49	6.11	628.49
Ce	34	43.44	13.52	1477.00
Nd	34	17.87	5.39	607.42
Sm	34	3.23	0.87	109.92
Eu	34	0.75	0.17	25.61
Tb	34	0.55	0.11	18.77
Yb	34	1.53	0.42	52.05
Lu	34	0.24	0.07	8.31

Minima and Maxima

Variable	Minimum	Maximum
al-alk	5.86	17.16
NIG Ti	1.22	3.97
NIG Fm	15.70	45.74
NIG K	0.18	0.52
NIG Mg	0.49	0.67
NIGSI	136.67	591.08
CaO	1.11	15.42
K_2O	0.58	2.30
Ba	223.00	1116.00
Sr	73.00	246.00
Zr	105.00	1293.00
Y	10.00	34.00
Cu	5.00	90.00
Ni	30.00	160.00
V	24.00	97.00
Zn	34.00	120.00
Ag	0.10	1.00
Au	5.00	37.00
As	2.00	9.00
Cs	7.00	43.00
Cr	153.00	1100.00
Cs	0.50	4.10
Hf	0.34	28.00
Rb	20.00	110.00
Sb	0.20	13.00
Sc	3.70	16.00
Th	3.40	21.00
U	0.60	3.50
La	10.70	45.70
Ce	26.00	103.00
Nd	10.00	40.00
Sm	1.80	6.50
Eu	0.50	1.30
Tb	0.40	1.00
Yb	0.80	3.10
Lu	0.15	0.52

Correlation Coefficients

	al-alk	NIG Ti	NIG Fm	NIG K	NIG Mg	NIG Si
al-alk	1.00	0.67	0.91	0.15	0.24	0.55
NIG Ti	0.67	1.00	0.65	-0.21	-0.21	0.36
NIG Fm	0.91	0.65	1.00	0.10	0.47	0.62
NIG K	0.15	-0.21	0.10	1.00	0.33	-0.18
NIG Mg	0.24	-0.21	0.47	0.33	1.00	0.31
NIG Si	0.55	0.36	0.62	-0.18	0.31	1.00
CaO	-0.84	-0.63	-0.89	0.02	-0.38	-0.82
K_2O	0.17	-0.08	0.11	0.87	0.27	-0.36
Ba	0.02	0.06	0.04	-0.11	-0.12	0.01
Sr	-0.28	0.15	-0.43	-0.31	-0.72	-0.26
Zr	0.03	0.71	0.02	-0.41	-0.58	-0.04
Y	0.06	0.47	-0.07	-0.06	-0.59	-0.47
Cu	0.48	0.31	0.42	0.28	0.04	0.26
Ni	0.47	0.32	0.54	0.12	0.27	-0.05
V	0.45	0.47	0.38	0.34	-0.15	-0.14
Zn	0.34	0.24	0.33	0.05	0.11	0.14
Ag	0.14	0.05	0.06	-0.10	-0.16	0.42
Au	0.22	0.11	0.16	0.05	-0.07	0.43
As	0.24	0.26	0.09	-0.30	-0.29	-0.11
Co	0.32	0.34	0.25	0.35	-0.08	-0.08
Cr	-0.05	0.59	0.09	-0.37	-0.29	0.06
Cs	0.22	0.10	0.10	0.61	0.07	-0.17
Hf	0.01	0.71	0.03	-0.41	-0.54	-0.03
Rb	0.26	0.07	0.20	0.65	0.22	-0.30
Sb	0.11	0.06	0.01	-0.21	-0.21	0.44
Sc	0.10	0.05	0.04	0.29	-0.07	-0.46
Th	0.18	0.76	0.13	-0.28	-0.55	-0.05
U	0.29	0.62	0.19	-0.05	-0.41	-0.18
La	0.13	0.65	0.05	-0.21	-0.59	-0.28
Ce	0.13	0.66	0.07	-0.18	-0.55	-0.29
Nd	0.14	0.64	0.07	-0.22	-0.49	-0.29
Sm	0.21	0.62	0.10	-0.11	-0.55	-0.35
Eu	0.09	0.52	0.01	-0.13	-0.49	-0.42
Tb	0.05	0.10	0.02	0.30	-0.01	-0.35
Yb	0.17	0.66	0.09	-0.19	-0.55	-0.34
Lu	0.14	0.68	0.11	-0.17	-0.47	-0.30

Correlation Coefficients (cont.)

	CaO	K_2O	Ba	Sr	Zr	Y
al-alk	-0.84	0.17	0.02	-0.28	0.03	0.06
NIG Ti	-0.63	-0.08	0.06	0.15	0.71	0.47
NIG Fm	-0.89	0.17	0.04	-0.43	0.02	-0.07
NIG K	0.02	0.87	-0.11	-0.31	-0.41	-0.06
NIG Mg	-0.38	0.27	-0.17	-0.72	-0.58	-0.59
NIG Si	-0.82	-0.36	0.01	-0.26	-0.04	-0.47
CaO	1.00	-0.01	-0.07	0.35	-0.02	0.26
K_2O	-0.01	1.00	-0.01	-0.26	-0.33	0.04
Ba	-0.07	-0.01	1.00	0.20	-0.08	-0.04
Sr	0.35	-0.26	0.20	1.00	0.49	0.52
Zr	-0.02	-0.33	-0.08	0.49	1.00	0.72
Y	0.26	0.04	-0.04	0.52	0.72	1.00
Cu	-0.30	0.19	0.22	-0.11	-0.07	0.01
Ni	-0.33	0.26	-0.06	-0.35	0.03	0.14
V	-0.20	0.45	0.05	-0.03	0.20	0.39
Zn	-0.29	0.12	0.09	-0.04	0.04	0.09
Ag	-0.18	-0.23	0.54	0.29	-0.11	-0.19
Au	-0.22	-0.13	0.47	0.11	-0.11	-0.18
As	0.06	-0.27	-0.16	0.36	0.25	0.42
Co	-0.12	0.39	-0.09	0.03	0.07	0.18
Cr	-0.08	-0.35	-0.14	0.22	0.85	0.45
Cs	0.00	0.63	0.04	-0.03	-0.12	0.16
Hf	-0.02	-0.34	-0.09	0.46	0.98	0.68
Rb	-0.11	0.85	-0.03	-0.28	-0.22	0.03
Sb	-0.14	-0.35	0.36	0.26	-0.07	-0.18
Sc	0.15	0.44	-0.02	-0.17	0.04	0.29
Th	-0.07	-0.21	-0.13	0.47	0.94	0.77
U	-0.03	0.02	-0.13	0.31	0.72	0.79
La	0.12	-0.12	-0.12	0.49	0.87	0.91
Ce	0.10	-0.08	-0.10	0.49	0.87	0.93
Nd	0.07	-0.06	-0.15	0.51	0.82	0.88
Sm	0.11	0.00	-0.09	0.48	0.77	0.95
Eu	0.18	0.04	-0.02	0.47	0.70	0.93
Tb	0.20	0.29	-0.20	0.31	0.19	0.55
Yb	0.10	-0.03	-0.09	0.45	0.81	0.91
Lu	0.07	-0.02	-0.07	0.45	0.84	0.88

Correlation Coefficients (cont.)

	Cu	Ni	V	Zn	Ag	Au
al-alk	0.48	0.47	0.45	0.34	0.14	0.22
NIG Ti	0.31	0.32	0.47	0.24	0.05	0.11
NIG Fm	0.42	0.54	0.38	0.33	0.06	0.16
NIG K	0.28	0.12	0.34	0.05	-0.10	0.05
NIG Mg	0.04	0.27	-0.15	0.11	-0.16	-0.07
NIG Si	0.26	-0.05	-0.14	0.14	0.42	0.43
CaO	-0.30	-0.33	-0.20	-0.29	-0.18	-0.22
K_2O	0.19	0.26	0.45	0.12	-0.23	-0.13
Ba	0.22	-0.06	0.05	0.09	0.54	0.47
Sr	-0.11	-0.35	-0.03	-0.04	0.29	0.11
Zr	-0.07	0.03	0.20	0.04	-0.11	-0.11
Y	0.01	0.14	0.39	0.09	-0.19	-0.18
Cu	1.00	-0.12	0.21	0.42	0.48	0.70
Ni	-0.12	1.00	0.42	0.07	-0.36	-0.33
V	0.21	0.42	1.00	-0.18	-0.05	0.07
Zn	0.42	0.07	-0.18	1.00	0.11	0.18
Ag	0.48	-0.36	-0.05	0.11	1.00	0.91
Au	0.70	-0.33	0.07	0.18	0.91	1.00
As	0.07	0.30	0.10	0.15	-0.05	-0.11
Co	0.15	0.18	0.81	-0.32	-0.06	0.04
Cr	-0.14	0.14	0.16	0.00	-0.18	-0.12
Cs	0.42	-0.12	0.47	0.12	0.04	0.11
Hf	-0.07	0.04	0.19	0.03	-0.11	-0.11
Rb	0.20	0.22	0.41	0.21	-0.23	-0.18
Sb	0.54	-0.44	-0.14	0.15	0.89	0.87
Sc	-0.03	0.43	0.76	-0.23	-0.35	-0.25
Th	-0.03	0.17	0.41	-0.01	-0.10	-0.08
U	0.20	0.22	0.43	0.26	-0.02	0.00
La	0.04	0.19	0.45	0.02	-0.14	-0.11
Ce	0.07	0.20	0.39	0.11	-0.17	-0.14
Nd	-0.04	0.27	0.39	0.10	-0.23	-0.21
Sm	0.08	0.29	0.50	0.08	-0.18	-0.14
Eu	0.02	0.24	0.36	0.11	-0.25	-0.24
Tb	0.10	0.22	0.08	0.34	-0.16	-0.11
Yb	0.07	0.27	0.44	0.11	-0.24	-0.21
Lu	0.13	0.21	0.43	0.14	-0.14	-0.08

Correlation Coefficients (cont.)

	As	Co	Cr	Cs	Hf	Rb
al-alk	0.24	0.32	-0.05	0.22	0.01	0.26
NIG Ti	0.26	0.34	0.59	0.10	0.71	0.07
NIG Fm	0.09	0.25	0.09	0.10	0.03	0.20
NIG K	-0.30	0.35	-0.37	0.61	-0.41	0.65
NIG Mg	-0.29	-0.08	-0.29	0.07	-0.54	0.22
NIG Si	-0.11	-0.08	0.06	-0.17	-0.03	-0.30
CaO	0.06	-0.12	-0.08	0.00	-0.02	-0.11
K_2O	-0.27	0.39	-0.35	0.63	-0.34	0.85
Ba	-0.16	-0.09	-0.14	0.04	-0.09	-0.03
Sr	0.36	0.03	0.22	-0.03	0.46	-0.28
Zr	0.25	0.07	0.85	-0.12	0.98	-0.22
Y	0.42	0.18	0.45	0.16	0.68	0.04
Cu	0.07	0.15	-0.14	0.42	-0.07	0.20
Ni	0.30	0.18	0.14	-0.12	0.04	0.22
V	0.10	0.81	0.16	0.47	0.19	0.41
Zn	0.15	-0.32	0.00	0.12	0.03	0.21
Ag	-0.05	-0.06	-0.18	0.04	-0.11	-0.23
Au	-0.11	0.04	-0.12	0.11	-0.11	-0.18
As	1.00	0.08	0.06	-0.07	0.25	-0.29
Co	0.08	1.00	0.04	0.69	0.11	0.37
Cr	0.06	0.04	1.00	-0.23	0.87	-0.27
Cs	-0.07	0.69	-0.23	1.00	-0.09	0.61
Hf	0.25	0.11	0.87	-0.09	1.00	-0.21
Rb	-0.29	0.37	-0.27	0.61	-0.21	1.00
Sb	0.02	-0.08	-0.12	0.01	-0.06	-0.31
Sc	0.10	0.45	0.06	0.38	0.02	0.38
Th	0.34	0.32	0.78	0.00	0.94	-0.13
U	0.34	0.13	0.52	0.16	0.72	0.17
La	0.46	0.30	0.65	0.07	0.85	-0.08
Ce	0.46	0.22	0.66	0.10	0.85	-0.03
Nd	0.48	0.22	0.65	0.07	0.81	-0.02
Sm	0.55	0.30	0.53	0.12	0.74	0.01
Eu	0.48	0.12	0.46	0.16	0.67	0.05
Tb	0.43	-0.06	0.09	0.21	0.18	0.15
Yb	0.50	0.27	0.61	0.10	0.80	0.04
Lu	0.40	0.25	0.67	0.11	0.84	0.04

Correlation Coefficients (cont.)

	Sb	Sc	Th	U	La	Ce
al-alk	0.11	0.10	0.18	0.29	0.13	0.14
NIG Ti	0.06	0.05	0.76	0.62	0.65	0.66
NIG Fm	0.01	0.04	0.13	0.19	0.05	0.07
NIG K	-0.21	0.29	-0.28	-0.05	-0.21	-0.18
NIG Mg	-0.21	-0.07	-0.55	-0.41	-0.59	-0.55
NIG Si	0.44	-0.46	-0.05	-0.18	-0.28	-0.29
CaO	-0.14	0.15	-0.07	-0.03	0.12	0.10
K_2O	0.35	0.44	-0.21	0.02	-0.12	-0.08
Ba	0.36	-0.02	-0.13	-0.13	-0.12	-0.10
Sr	0.26	-0.17	0.47	0.31	0.49	0.49
Zr	-0.07	0.04	0.94	0.72	0.87	0.87
Y	-0.18	0.29	0.77	0.79	0.91	0.93
Cu	0.54	-0.03	-0.03	0.20	0.04	0.07
Ni	-0.44	0.43	0.17	0.22	0.19	0.20
V	-0.14	0.76	0.41	0.43	0.45	0.39
Zn	0.15	-0.23	-0.01	0.26	0.02	0.11
Ag	0.89	-0.35	-0.10	-0.02	-0.14	-0.17
Au	0.87	-0.25	-0.08	0.00	-0.11	-0.14
As	0.02	0.10	0.34	0.34	0.46	0.46
Co	-0.08	0.45	0.32	0.13	0.30	0.22
Cr	-0.12	0.06	0.78	0.52	0.65	0.66
Cs	0.01	0.38	0.00	0.16	0.07	0.10
Hf	-0.06	0.02	0.94	0.72	0.85	0.85
Rb	-0.31	0.38	-0.13	0.17	-0.08	-0.03
Sb	1.00	-0.47	-0.07	-0.03	-0.10	-0.13
Sc	-0.47	1.00	0.14	0.36	0.27	0.22
Th	-0.07	0.14	1.00	0.75	0.94	0.92
U	-0.03	0.36	0.75	1.00	0.82	0.84
La	-0.10	0.27	0.94	0.82	1.00	0.98
Ce	-0.13	0.22	0.92	0.84	0.98	1.00
Nd	-0.19	0.25	0.88	0.76	0.93	0.95
Sm	-0.16	0.32	0.86	0.82	0.97	0.97
Eu	-0.21	0.25	0.73	0.76	0.87	0.91
Tb	-0.19	0.08	0.26	0.50	0.43	0.50
Yb	-0.18	0.28	0.86	0.80	0.94	0.96
Lu	-0.09	0.26	0.88	0.83	0.95	0.97

Correlation Coefficients (cont.)

	Nd	Sm	Eu	Tb	Yb	Lu
al-alk	0.14	0.21	0.09	0.05	0.17	0.14
NIG Ti	0.64	0.62	0.52	0.10	0.66	0.68
NIG Fm	0.07	0.10	0.01	0.02	0.09	0.11
NIG K	-0.22	-0.11	-0.13	0.30	-0.19	-0.17
NIG Mg	-0.49	-0.55	-0.49	-0.01	-0.56	-0.47
NIG Si	-0.29	-0.35	-0.42	-0.35	-0.34	-0.30
CaO	0.07	0.11	0.18	0.20	0.10	0.07
K_2O	-0.06	0.00	0.04	0.29	-0.03	-0.02
Ba	-0.15	-0.09	-0.02	-0.20	-0.09	-0.07
Sr	0.51	0.48	0.47	0.31	0.45	0.45
Zr	0.82	0.77	0.70	0.19	0.81	0.84
Y	0.88	0.95	0.93	0.55	0.91	0.88
Cu	-0.04	0.08	0.02	0.10	0.07	0.13
Ni	0.27	0.29	0.24	0.22	0.27	0.21
V	0.39	0.50	0.36	0.08	0.44	0.43
Zn	0.10	0.08	0.11	0.34	0.11	0.14
Ag	-0.23	-0.18	-0.25	-0.16	-0.24	-0.14
Au	-0.21	-0.14	-0.24	-0.11	-0.21	-0.08
As	0.48	0.55	0.48	0.43	0.50	0.40
Co	0.22	0.30	0.12	-0.06	0.27	0.25
Cr	0.65	0.53	0.46	0.09	0.61	0.67
Cs	0.07	0.12	0.16	0.21	0.10	0.11
Hf	0.81	0.74	0.67	0.18	0.80	0.84
Rb	-0.02	0.01	0.05	0.15	0.04	0.04
Sb	-0.19	-0.16	-0.21	-0.19	-0.18	-0.09
Sc	0.25	0.32	0.25	0.08	0.28	0.26
Th	0.88	0.86	0.73	0.26	0.86	0.88
U	0.76	0.82	0.76	0.50	0.80	0.83
La	0.93	0.97	0.87	0.43	0.94	0.95
Ce	0.95	0.97	0.91	0.50	0.96	0.97
Nd	1.00	0.94	0.91	0.56	0.94	0.94
Sm	0.94	1.00	0.93	0.55	0.96	0.94
Eu	0.91	0.93	1.00	0.59	0.93	0.90
Tb	0.56	0.55	0.59	1.00	0.46	0.51
Yb	0.94	0.96	0.93	0.46	1.00	0.95
Lu	0.94	0.94	0.90	0.51	0.95	1.00

GOOSE TICKLE MAJOR AND TRACE ELEMENT PARAMETERS

Initial Factor Method: Principal Factors

Partial Correlations Controlling all other Variables

	ALALK	NIGTI	NIGFM	ZR
ALALK	1.00000	0.73307	0.46215	-0.24725
NIGTI	0.73307	1.00000	-0.21899	0.67530
NIGFM	0.46215	-0.21899	1.00000	0.06708
ZR	-0.24725	0.67530	0.06708	1.00000
CU	0.24421	-0.05548	0.24717	0.07159
NI	0.15239	-0.09436	0.34766	-0.06842
CO	0.30688	-0.11180	-0.00179	-0.03493
CR	-0.37849	0.23812	-0.18938	0.03093

	CU	NI	CO	CR
ALALK	0.24421	0.15239	0.30688	-0.37849
NIGTI	-0.05548	-0.09436	-0.11180	0.23812
NIGFM	0.24717	0.34766	-0.00179	-0.18938
ZR	0.07159	-0.06842	-0.03493	0.03093
CU	1.00000	-0.08824	-0.23104	0.33984
NI	-0.08824	1.00000	0.15269	0.72551
CO	-0.23104	0.15269	1.00000	0.09559
CR	0.33984	0.72551	0.09559	1.00000

Kaiser's Measure of Sampling Adequacy:
Over-all MSA = 0.65268151

ALALK	NIGTI	NIGFM	ZR
0.639433	0.623187	0.751817	0.678088

CU	NI	CO	CR
0.802332	0.626399	0.730372	0.434221

Prior Communality Estimates: SMC

ALALK	NIGTI	NIGFM	ZR
0.865987	0.860130	0.657516	0.656290

CU	NI	CO	CR
0.482789	0.688903	0.301640	0.665815

Eigenvalues of the Reduced Correlation Matrix:

Total = 5.17906894 Average = 0.64738362

	1	2	3	4
Eigenvalue	3.402513	1.234847	0.691171	0.249526
Difference	2.167666	0.543676	0.441645	0.268615
Proportion	0.6570	0.2384	0.1335	0.0482
Cumulative	0.6570	0.8954	1.0289	1.0770

	5	6	7	8
Eigenvalue	-0.019089	-0.085307	-0.115749	-0.178843
Difference	0.066218	0.030442	0.063094	
Proportion	-0.0037	-0.0165	-0.0223	-0.0345
Cumulative	1.0734	1.0569	1.0345	1.0000

3 factors will be retained by the PROPORTION criterion.

Factor Pattern

	FACTOR1	FACTOR2	FACTOR3
ALALK	0.87422	-0.29516	-0.25173
NIGTI	0.83771	-0.35471	0.25597
NIGFM	0.72281	0.01586	-0.39346
CU	0.64799	0.08336	0.04511
ZR	0.61600	-0.31691	0.44571
CO	0.38243	0.16290	-0.28614
CR	0.36126	0.68863	0.34948
NI	0.58132	0.64307	-0.05260

Variance explained by each factor

FACTOR1	FACTOR2	FACTOR3
3.402513	1.234847	0.691171

Final Communality Estimates: Total = 5.328531

ALALK	NIGTI	NIGFM	ZR
0.914741	0.893092	0.677513	0.678545

CU	NI	CO	CR
0.428877	0.754243	0.254665	0.726854

Rotation Method: Varimax

Orthogonal Transformation Matrix

	1	2	3
1	0.68217	0.65054	0.33383
2	-0.48789	0.06491	0.87049
3	0.54462	-0.75669	0.36168

Rotated Factor Pattern

	FACTOR1	FACTOR2	FACTOR3
NIGTI	0.88392	0.32825	0.06346
ZR	0.81757	0.04290	0.09098
CU	0.42594	0.39283	0.30519
NIGFM	0.27105	0.76897	0.11280
ALALK	0.60327	0.74004	-0.05613
CO	0.02556	0.47588	0.16598
CR	0.10080	0.01527	0.84644
NI	0.05416	0.45972	0.73482

Variance explained by each factor

FACTOR1	FACTOR2	FACTOR3
2.082310	1.840922	1.405299

Rotation Method: Varimax

Final Communality Estimates: Total = 5.328531

ALALK	NIGTI	NIGFM	ZR
0.914741	0.893092	0.677513	0.678545

CU	NI	CO	CR
0.428877	0.754243	0.254665	0.726854

GOOSE TICKLE TRACE ELEMENT PARAMETERS

Initial Factor Method: Principal Factors

Partial Correlations Controlling all other Variables

	NIGTI	ZR	Y	CU
NIGTI	1.00000	0.66837	-0.21873	0.28100
ZR	0.66837	1.00000	0.56139	-0.02674
Y	-0.21873	0.56139	1.00000	0.03010
CU	0.28100	-0.02674	0.03010	1.00000
NI	-0.00289	0.06508	-0.33710	0.18244
V	0.43674	-0.11832	0.26324	-0.01567
CO	-0.07792	-0.14204	0.06797	-0.08416
CR	-0.13058	0.14622	0.01064	0.10945

	NI	V	CO	CR
NIGTI	-0.00289	0.43674	-0.07792	-0.13058
ZR	0.06508	-0.11832	-0.14204	0.14622
Y	-0.33710	0.26324	0.06797	0.01064
CU	0.18244	-0.01567	-0.08416	0.10945
NI	1.00000	0.20151	0.19632	0.62352
V	0.20151	1.00000	0.57880	-0.05207
CO	0.19632	0.57880	1.00000	-0.05493
CR	0.62352	-0.05207	-0.05493	1.00000

Kaiser's Measure of Sampling Adequacy:
Over-all MSA = 0.6527072C

NIGTI	ZR	Y	CU
0.661573	0.624904	0.584841	0.852406

NI	V	CO	CR
0.629126	0.684040	0.621490	0.617600

Prior Communality Estimates: SMC

NIGTI	ZR	Y	CU
0.748917	0.748869	0.545542	0.333740

NI	V	CO	CR
0.640169	0.688519	0.514151	0.515578

Eigenvalues of the Reduced Correlation Matrix:
Total = 4.73548601 Average = 0.59193575

	1	2	3	4
Eigenvalue	2.929900	1.426833	0.729260	0.171803
Difference	1.503066	0.697574	0.557457	0.209358
Proportion	0.6187	0.3013	0.1540	0.0363
Cumulative	0.6187	0.9200	1.0740	1.1103

	5	6	7	8
Eigenvalue	-0.037555	-0.135024	-0.163275	-0.186456
Difference	0.097468	0.028251	0.023181	
Proportion	-0.0079	-0.0285	-0.0345	-0.0394
Cumulative	1.1024	1.0739	1.0394	1.0000

3 factors will be retained by the PROPORTION criterion.

Factor Pattern

	FACTOR1	FACTOR2	FACTOR3
NIGTI	0.82133	-0.25927	0.11527
V	0.77188	0.04535	-0.41475
ZR	0.73819	-0.43631	0.26667
CU	0.52356	0.12504	0.25903
NI	0.51549	0.67742	0.10967
CR	0.40066	0.55087	0.29682
Y	0.45107	-0.56635	-0.06779
CO	0.45908	0.26161	-0.54866

Variance explained by each factor

FACTOR1	FACTOR2	FACTOR3
2.929900	1.426833	0.729260

Final Communality Estimates: Total = 5.085993

NIGTI	ZR	Y	CU
0.755092	0.806401	0.528816	0.356847

NI	V	CO	CR
0.736663	0.769872	0.580221	0.552081

Rotation Method: Varimax

Ortnogonal Transformation Matrix

	1	2	3
1	0.73365	0.47472	0.48620
2	-0.63332	0.73703	0.23602
3	0.24630	0.48107	-0.84137

Rotated Factor Pattern

	FACTOR1	FACTOR2	FACTOR3
ZR	0.88358	0.15715	0.03156
NIGTI	0.79516	0.25427	0.24116
Y	0.67291	-0.23589	0.14268
NI	-0.02382	0.79675	0.31825
CR	0.01818	0.73900	0.07508
CU	0.36872	0.46532	0.06612
CO	0.03599	0.14681	0.74657
V	0.43542	0.20033	0.73495

Variance explained by each factor

FACTOR1	FACTOR2	FACTOR3
2.193537	1.604126	1.288329

Final Communality Estimates: Total = 5.085993

NIGTI	ZR	Y	CU
0.755092	0.806401	0.528816	0.356847

NI	V	CO	CR
0.736663	0.769872	0.580221	0.552081

LOWER HEAD MAJOR AND TRACE ELEMENT PARAMETERS

Initial Factor Method: Principal Factors

Partial Correlations Controlling all other Variables

	ALALK	NIGTI	NIGFM	ZR
ALALK	1.00000	0.30809	0.65920	0.16998
NIGTI	0.30809	1.00000	0.40791	0.75172
NIGFM	0.65920	0.40791	1.00000	-0.67555
ZR	0.16998	0.75172	-0.67555	1.00000
CU	0.11243	0.15691	0.01583	-0.13205
NI	0.15072	-0.14529	0.20772	0.02968
CO	0.08952	0.39295	-0.30223	-0.34702
CR	-0.65255	-0.00071	0.60851	0.60589

	CU	NI	CO	CR
ALALK	0.11243	0.15072	0.08952	-0.65255
NIGTI	0.15691	-0.14529	0.39295	-0.00071
NIGFM	0.01583	0.20772	-0.30223	0.60851
ZR	-0.13205	0.02968	-0.34702	0.60589
CU	1.00000	-0.41310	-0.03818	-0.01598
NI	-0.41310	1.00000	0.10794	0.12104
CO	-0.03818	0.10794	1.00000	0.10963
CR	-0.01598	0.12104	0.10963	1.00000

Kaiser's Measure of Sampling Adequacy:
Over-all MSA = 0.56914490

ALALK	NIGTI	NIGFM	ZR
0.640677	0.664392	0.535563	0.441954

CU	NI	CO	CR
0.709741	0.706217	0.461493	0.486577

Prior Communality Estimates: SMC

ALALK	NIGTI	NIGFM	ZR
0.928266	0.943667	0.930832	0.932479

CU	NI	CO	CR
0.407615	0.465307	0.268090	0.865792

Eigenvalues of the Reduced Correlation Matrix:
Total = 5.7420474 Average = 0.71775593

	1	2	3	4
Eigenvalue	3.176269	1.947176	0.589805	0.203008
Difference	1.229093	1.357371	0.386798	0.132313
Proportion	0.5532	0.3391	0.1027	0.0354
Cumulative	0.5532	0.8923	0.9950	1.0303

	5	6	7	8
Eigenvalue	0.070694	-0.036309	-0.060249	-0.148347
Difference	0.107003	0.023941	0.088098	
Proportion	0.0123	-0.0063	-0.0105	-0.0258
Cumulative	1.0427	1.0363	1.0258	1.0000

4 factors will be retained by the PROPORTION criterion.

Factor Pattern

	FACTOR1	FACTOR2	FACTOR3	FACTOR4
NIGTI	0.93579	0.25376	0.14911	0.08653
NIGFM	0.84785	-0.43311	-0.12211	-0.18944
ALALK	0.83410	-0.49651	0.03660	0.00829
ZR	0.49150	0.82486	0.11162	0.01442
CR	0.44984	0.79237	-0.11253	-0.11697
CU	0.34012	-0.32338	0.48804	-0.07961
NI	0.46025	-0.15927	-0.53588	0.04308
CO	0.33848	-0.10245	0.02920	0.37078

Variance explained by each factor

FACTOR1	FACTOR2	FACTOR3	FACTOR4
3.176269	1.947176	0.589805	0.203008

Final Communality Estimates: Total = 5.916258

ALALK	NIGTI	NIGFM	ZR
0.943651	0.969811	0.957232	0.934625

CU	NI	CO	CR
0.464776	0.526222	0.263396	0.856547

Rotation Method: Varimax

Orthogonal Transformation Matrix

	1	2	3	4
1	0.51892	0.60971	0.50012	0.32994
2	0.84619	-0.33993	-0.39823	-0.09906
3	0.06834	-0.69166	0.71342	0.08925
4	-0.10003	-0.18523	-0.28691	0.93454

Rotated Factor Pattern

	FACTOR1	FACTOR2	FACTOR3	FACTOR4
ZR	0.95922	-0.06060	-0.00718	0.10389
CR	0.90794	0.10442	-0.13729	-0.04943
NIGTI	0.70187	0.36513	0.44850	0.37779
NIGFM	0.08408	0.78372	0.56374	0.13471
NI	0.06312	0.69743	-0.10106	0.16006
ALALK	0.01436	0.65049	0.63861	0.33540
CU	-0.05583	-0.00551	0.66990	0.11341
CO	0.05385	0.15232	0.12453	0.47094

Variance explained by each factor

FACTOR1	FACTOR2	FACTOR3	FACTOR4
2.254350	1.694877	1.420164	0.546868

Final Communality Estimates: Total = 5.916258

ALALK	NIGTI	NIGFM	ZR
0.943651	0.969811	0.957232	0.934625

CU	NI	CO	CR
0.464776	0.526222	0.263396	0.856547

LOWER HEAD TRACE ELEMENT PARAMETERS

Initial Factor Method: Principal Factors

Partial Correlations Controlling all other Variables

	NIGTI	ZR	Y	CU
NIGTI	1.00000	0.69592	-0.45228	0.56678
ZR	0.69592	1.00000	0.79093	-0.34032
Y	-0.45228	0.79093	1.00000	0.14744
CU	0.56678	-0.34032	0.14744	1.00000
NI	0.54399	-0.49582	0.28143	-0.55161
V	0.06799	-0.13896	0.32012	0.37468
CO	0.17433	-0.06223	-0.10887	-0.39538
CR	-0.27729	0.78720	-0.58864	-0.01288

	NI	V	CO	CR
NIGTI	0.54399	0.06799	0.17433	-0.27729
ZR	-0.49582	-0.13896	-0.06223	0.78720
Y	0.28143	0.32012	-0.10887	-0.58864
CU	-0.55161	0.37468	-0.39538	-0.01288
NI	1.00000	0.40261	-0.41692	0.24005
V	0.40261	1.00000	0.84066	0.27078
CO	-0.41692	0.84066	1.00000	-0.15357
CR	0.24005	0.27078	-0.15357	1.00000

Kaiser's Measure of Sampling Adequacy:
Over-all MSA = 0.45391882

NIGTI	ZR	Y	CU
0.541373	0.462836	0.451962	0.180582

NI	V	CO	CR
0.212448	0.553799	0.442432	0.535246

Prior Communality Estimates: SMC

NIGTI	ZR	Y	CU
0.818509	0.940667	0.760234	0.525169

NI	V	CO	CR
0.570989	0.854525	0.781688	0.832617

Eigenvalues of the Reduced Correlation Matrix:
Total = 6.08439825 Average = 0.76054978

	1	2	3	4
Eigenvalue	3.238518	1.561873	0.688423	0.467338
Difference	1.676644	0.873451	0.221085	0.137605
Proportion	0.5323	0.2567	0.1131	0.0768
Cumulative	0.5323	0.7890	0.9021	0.9789

	5	6	7	8
Eigenvalue	0.329732	0.034289	-0.083573	-0.152202
Difference	0.295443	0.117862	0.068629	
Proportion	0.0542	0.0056	-0.0137	-0.0250
Cumulative	1.0331	1.0388	1.0250	1.0000

5 factors will be retained by the PROPORTION criterion.

Factor Pattern

	FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
ZR	0.83840	-0.51586	0.08480	-0.09873	-0.02947
NIGTI	0.83665	0.03034	0.17562	0.32489	-0.03504
CR	0.72433	-0.46407	-0.10099	0.06765	-0.28360
V	0.70204	0.63092	-0.06662	-0.07286	-0.00743
Y	0.69656	-0.19898	0.02309	-0.27321	0.41382
CO	0.46613	0.68142	-0.05386	-0.29717	-0.19338
CU	0.12550	0.34003	0.60108	0.21961	0.08563
NI	0.31602	0.24878	-0.52060	0.36190	0.17658

Variance explained by each factor

FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
3.238518	1.561873	0.688423	0.467338	0.329732

Final Communality Estimates: Total = 6.285884

NIGTI	ZR	Y	CU
0.838532	0.986832	0.771213	0.548228

NI	V	CO	CR
0.594937	0.900716	0.810209	0.835216

Rotation Method: Varimax

Orthogonal Transformation Matrix

	1	2	3	4	5
1	0.73965	0.45056	0.40053	0.16392	0.25025
2	-0.50908	0.73573	-0.17662	0.32591	0.24924
3	0.05466	-0.09139	0.05838	0.78645	-0.60560
4	0.16479	-0.41002	-0.43028	0.46301	0.63656
5	-0.40449	-0.28148	0.78729	0.18446	0.32141

Rotated Factor Pattern

	FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
CR	0.89234	0.04624	0.11380	-0.13293	0.07867
ZR	0.88302	0.03924	0.45114	-0.01515	-0.04244
NIGTI	0.68069	0.25988	0.17262	0.42911	0.30613
CO	0.02418	0.89256	0.03883	0.08287	0.06778
V	0.18543	0.81855	0.19137	0.23321	0.32451
Y	0.40536	0.16088	0.75884	0.01732	0.06983
CU	-0.04588	0.13763	-0.00178	0.72159	-0.08054
NI	0.06685	0.17491	0.03555	-0.07641	0.74349

Variance explained by each factor

FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
2.245204	1.613307	0.861514	0.790120	0.775739

Final Communality Estimates: Total = 6.285884

NIGTI	ZR	Y	CU
0.838532	0.986832	0.771213	0.548228

NI	V	CO	CR
0.594937	0.900716	0.810209	0.835216